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PHYSICS

L. JACOB

HIGH VOLTAGE PHYSICS

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HIGH VOLTAGE PHYSICS

by

L. JACOB, M.Sc., A.R.C.Sc.I.

A MEMBER OF THE RESEARCH LABORATORIES OF THE GENERAL
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AUTHOR'S PREFACE

THIS book gives a survey in outline of the Physics of high voltage phenomena. Most of the results so far obtained on dielectrics are to some extent empirical, owing to the complex structure and behaviour of the materials examined. Co-operation of the physical and colloid chemist with the physicist would thus be profitable in helping to elucidate some of the more fundamental aspects of dielectric behaviour. I have purposely refrained from giving any detailed discussion of the radioactive α and β radiations (considered as high velocity particles), as I anticipate they will be amply dealt with in this series.

I wish to express my best thanks to my colleagues—Mr. B. S. Gossling, for his reading and criticism of the bulk of the manuscript, and Dr. W. G. Thompson, for reading the proofs. I also wish to express my indebtedness to the Director of these laboratories for permission to publish Fig. 23 from some unpublished work done here, and to the McGraw-Hill Book Co. for permission to reproduce Figs. 22, 27, 32 from Peek's " Dielectric Phenomena."

<div align="right">L. JACOB</div>

RESEARCH LABORATORIES
WEMBLEY, *May*, 1934

CONTENTS

HIGH VOLTAGE PHYSICS

CHAPTER I

PRODUCTION AND MEASUREMENT OF HIGH VOLTAGE

THE term high voltage is used to denote any voltage from about 1 kilovolt to 1000 kilovolts and over, and this book is devoted to describing the effects of the application of such voltages to matter in its various forms and under different physical conditions.

The high voltage is usually produced by machines of one kind or another, which are so arranged that as a result of their operation, electromotive forces are generated at their terminals by the well-known effects of electromagnetic or electrostatic induction.

Among those working on the former principle are the direct-current dynamo, static transformers, induction coils, including Tesla coils, while the old Wimshurst machine represents the principles on which the electrostatic generator depends. The high voltage is produced as continuous and unidirectional by the use of the direct-current dynamo and electrostatic generator, and as alternating in character by the transformer and induction coil ; however, it is possible to convert this alternating voltage into a continuous and unidirectional one by suitable rectification and smoothing.

Mention should of course be made here of the building up of a high voltage by the use of a very large number of low voltage accumulators connected in series. Such a

1

battery giving 100 KV. and 40 mA. has been used at Harvard University, where extremely high precision results were aimed at. The initial expense and the care necessary to keep the batteries in good condition really preclude their use to any large extent, particularly since reliably constant voltage can now be obtained by a simpler method, and since the present-day tendency is for higher and higher voltage.

Fig. 1.—Electrostatic generator.

Direct-current machines have been made to give up to about 20 KV. with 250 mA. output. Above this voltage, difficulties in design are introduced owing to insulation problems ; their sphere of usefulness is thus rather limited.

Electrostatic Generators.— The principles of electrostatic induction were applied very long ago to the production of high voltages, and found expression in a practical form in the Wimshurst and Voss influence machines. Their chief disadvantages, in addition to their unreliability, were their low power output and bad regulation, as the voltage decreased rapidly when the load increased. No notable advances in this direction had been introduced until just very recently, when Van de Graaf, Compton and Van Atta built an ingenious generator on electrostatic principles for use in nuclear investigations.
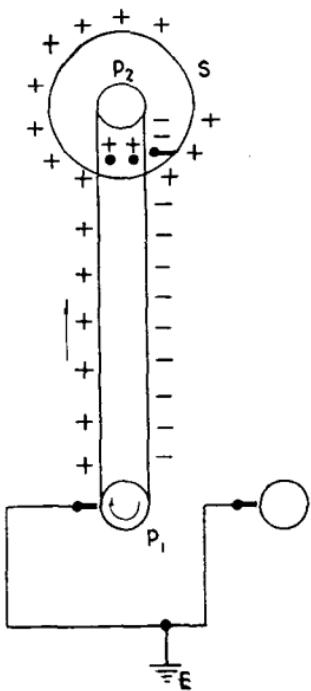
The experimental model, which generated 1500 KV. with an output of 25 microamps, consisted of two spherical electrodes S (only one shown), 24 ins. in diameter, mounted on 7-ft. pyrex rods. Silk ribbon belts, 2·2 ins. wide,

travelling at 3500 ft./min. are frictionally charged positively when passing round pulley P_1, and give up this charge to the sphere S (which acts as a huge Faraday pail) when they enter it.

The same belt, passing out of the sphere round the pulley, P_2 is inductively given a negative charge, thus doubling the current output. It is clear that the voltage limit is set only by the ability of the surrounding medium in contact with the spheres to withstand rupture owing to the maximum charge density on the spheres. In the case of air, a charge density on the sphere giving a gradient of 30 KV./cm. out from its surface is sufficient to cause breakdown of the air. The current is similarly limited by the maximum surface charge density on the belts, hence, the output varies as the cube of the breakdown strength of the surrounding medium.

Their large generator, having aluminium-alloy spheres 15 ft. in diameter, is expected to provide ten million volts with an output of 20 kilowatts.

Transformers.—Transformers are the most widely used of all types of generators for the production of voltages up to 200 KV. If D.C. is required, the voltage is usually rectified either by a high voltage thermionic rectifying valve or by a suitable mechanical rectifier. The advantages to be gained by using transformers are, that the wave-form is accurately known, and that the voltage control is smooth, usually on the primary side by resistance or choke, or by varying the alternator field supplying the primary. In combination with condensers and rectifiers, the voltage may be doubled or trebled, as shown in the later diagrams.

Transformers are made either as—

(1) Iron core. These are limited in single units to give up to about 1000 KV. by mechanical and insulation problems, and can, when connected in cascade, be made to give over 2000 KV. ;

(2) Air core or Tesla coil, which gives a very high voltage at high frequency.

In the cascade connection, the primary of No. 2 is

connected to a tapping off the secondary of No. 1.
This raises the potential of the primary of No. 2
to V above earth; the secondary of No. 2 will thus be at 2V above earth, and if n transformers be connected in this way, the voltage at the terminals of the nth will be nV above earth. When used with condensers and rectifiers to give D.C., the ripple can be cut down to a very
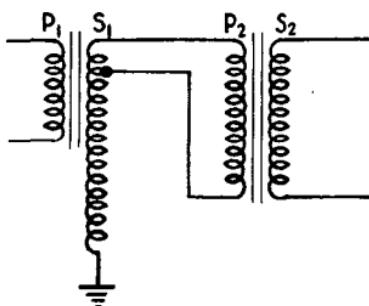
FIG. 2.—Cascade connection.

small amount by choosing suitable values of capacity.
Thus, Fortescue gives in the case of half-wave rectification the relation

$$C = \frac{I_0}{V_0} \cdot \frac{1}{\alpha f} \cdot \frac{\pi + 2\theta}{2\pi}$$

for the required capacity for any permissible voltage
variation αV_0 on the condenser (output), where

V_0 = output voltage,
I_0 = output current whose maximum value is $\frac{1}{2}$
      saturation emission of rectifier,
f = frequency,
$\theta = \sin^{-1} \dfrac{V_0}{V}$, where V = peak transformer volts.

In the case of the biphase circuit the capacity is given
by

$$C = \frac{I_0}{V_0} \cdot \frac{1}{\alpha f} \cdot \frac{\theta}{\pi}$$

and for the same smoothing is considerably less.
In the case of a rectified three-phase supply, hardly
any smoothing capacity is required, as the output ripple
is only about ± 30 per cent. from the mean value;
with six-phase this is decreased to about ± 7 per cent.

No difficulty arises in rectification, as thermionic rectifiers giving good life performance are now available capable of rectifying several hundred milliamperes up to 220 KV. peak reverse across the valve. These have to a very large extent superseded the old mechanical rectifier first introduced by Snook, which, besides being noisy and irregular in operation, had a low efficiency (only 50 per cent. of constant potential D.C. at 120 KV. peak and 5 mA.).

(a) Half wave circuit.

(b) Biphase full wave circuit.

(c) Graëtz full wave circuit.
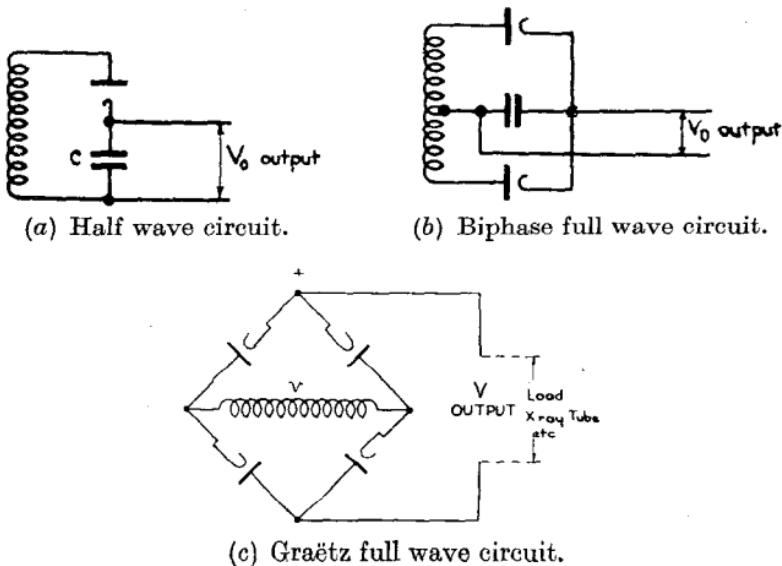
FIG. 3.

The Tesla coil is, in a way, a modification of the popular induction coil which was used extensively in the early days of X-ray technology. Even to-day, where waveform and power output are of no consequence, the induction coil can be used to advantage for laboratory work ; the largest made is oil immersed and gives about 10 mA. continuously at 250 KV. The Tesla coil, or air core transformer, has been recently developed by Breit, Tuve and Dahl for work in connection with the acceleration of atomic nuclei under the very high voltage

produced by the coil.   The principle on which it works is already well known.   In their case, the transformer T charged the condenser C 120 times per sec. through the mechanical rectifier MR.   When the voltage across C reaches the sparkover voltage of about 30 KV. for the gap G, a train of oscillatory discharges is set up in the circuit CPG, the resonant frequency being about 100,000 cycles per sec.   The changing flux in the primary P, consisting of a few turns of copper tubing of small inductance, induces a voltage (limited by corona) of about three million volts on the secondary S, which has a very large inductance, and is wound with 5000–7000 turns of No. 40 B.S. wire as a single layer on pyrex glass of 8 cms. diam. and 1 metre long.   Both primary and secondary were immersed in transformer oil at atmo-

FIG. 4.—Tesla coil.

spheric pressure in order to avoid corona loss and sparkover which would ordinarily occur if they were situated in air. By increasing the oil pressure to about 35 atmospheres, the volt-age obtained from the secondary exceeded five million volts, being limited at this stage by trouble with the insulation between turns.
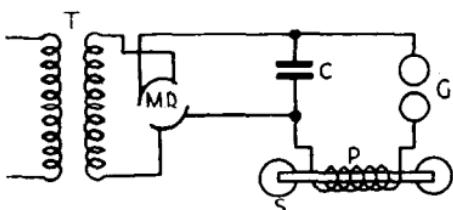
The instantaneous power available was over 1000 KW. with an instantaneous current of 250 mA.

Voltage Multiplying Circuits.—The multiplication of voltage is achieved by the combined use of thermionic rectifiers and condensers, as shown in Fig. 5.   It is possible in this way to obtain either a pulsating or con-tinuous voltage supply, depending on requirements, the only drawback being that the current output is somewhat limited, owing to the fact that the charged condensers have to supply the output current.   The wave-form depends on the current drawn from the condensers, but the ripple can be made less than 5 per cent. with suitable

choice of running conditions. These circuits are in much favour for cable testing, medical radiography, etc., and
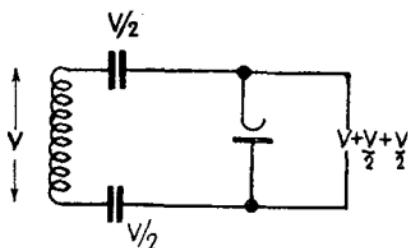
Villard circuit, voltage doubler:
pulsating.
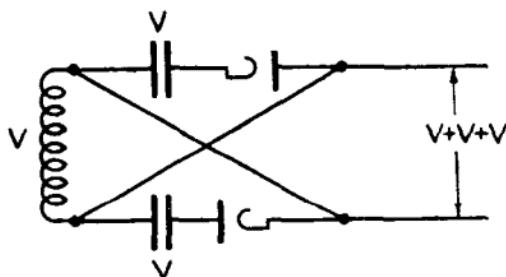
Witka circuit, voltage trebler:
pulsating.
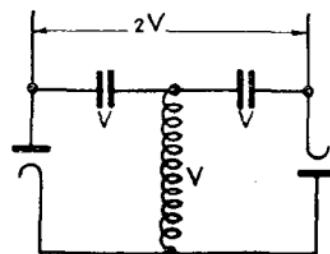
Greinacher circuit, voltage
doubler: D.C.

FIG. 5.

do not occupy much space when assembled. It should be especially observed that in all these types of circuits, the thermionic rectifying valve is called on to withstand a maximum peak reverse pressure of double the transformer peak voltage.

Further application of the above principles is found in the impulse generator developed by Marx, and used for testing insulating properties of materials. Here, the condensers are charged
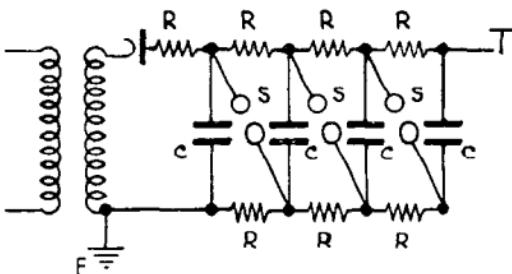
FIG. 6.—Marx impulse circuit.

in parallel through the rectifier and resistances to the voltage of the transformer, and when the voltage rises sufficiently to break down the spark gaps S, the condensers are automatically connected in series through the gaps, giving an impulse voltage of short duration, whose value is not far removed from nV, where n is the number of condensers. The external circuit constants can be so chosen as to give any voltage wave-shape desired.

Just very recently D'Arsonval in France has announced an impulse generator giving three million volts, and having 100 condensers of 0·5 μF, each charged to 30 KV. The total energy of discharge was 22,500 joules, giving a maximum instantaneous current of 3000 amps. and a maximum instantaneous power of nine million kilowatts.

**Measurement of High Voltage.**—The accurate measurement of high voltage has always been one of the most difficult measurements to make, because it brings in such factors as spacing, corona, etc., which have not to be considered in the low voltage case. New types of measurement, depending on entirely different principles from those for low voltages, have been developed, but they are usually not capable of the same accuracy, even though the greatest possible precautions are taken.

Using the **transformer ratio,** the high voltage is calculated by multiplying the primary voltage as read by an A.C. voltmeter by the ratio of transformation. An accuracy of 1 per cent. can be claimed if the secondary crest factor remains constant throughout. This is not always the case, owing to the distortion produced by the method used for controlling the primary volts, e.g. auto-transformer control on the primary invariably introduces distortion for some tappings.

The **oscillograph** is a convenient instrument with which to get the wave-shape and voltage values when the frequency is below 1000 cycles. The moving-coil element is connected in the low voltage side in series with a resistance to one line and then to earth. Where

the frequency is above 1000 cycles, the cathode ray type is used, having the further advantage that transients may now be recorded. Use of a **high resistance** in series with a milliameter is a convenient method for calibration purposes which has been used with success, and gives an accuracy to within 1 per cent.

The D.C. voltage is obtained by multiplying the value of the current by the value of the resistance. Wire-wound resistances of total value up to 10 megohms, and consisting of 100 units of 100,000 ohms of constantan wire of diameter 0·0015 in. have been used. These units are readily replaceable when checked periodically, and do not alter appreciably over any length of time. Recently Bowdler has described a suitable resistance, consisting of a thin layer of carbon on a porcelain tube, and having all values of resistance up to 10 megohms and over. These have a negative temperature coefficient of 3–4 parts in 10,000 per °C., and are rated from $\frac{1}{2}$–140 watts. With A.C. the phase error at 50 cycles of such a resistance of 100 megohms did not differ from its true value by more than 1 part in 1000.

The **sphere gap** is the simplest, and probably the most widely used of all methods, even for the very highest voltages. It consists essentially of two equal sized metallic spheres of steel, phosphor bronze, brass, copper, etc., mounted on a rigid framework, one of which is fixed and the other movable, the distance between the two spheres being read on an engraved scale on the arm of the movable sphere, the standard sizes ranging from 0·5 cm. to about 200 cms. in diameter. The voltage to be measured is applied across the gap, and the distance between the spheres for sparkover gives a measure of the peak value of the applied voltage.

The following precautions must be taken for best accuracy :—

    (1) the distance between the spheres should not exceed the radius of either—this is to keep the field between the spheres uniform and to prevent corona discharge ;

 (2) the surfaces should be cleanly polished, preferably with high-speed rotating pads (metal polish finishing with chamois leather is also good), for consistent sparkover;

 (3) insertion of series resistance next to the gap, preferably in each arm (about 1 ohm per volt to be measured). This minimises overvoltages, cuts out oscillations in the subsequent sparkover, limits the current, and prevents pitting of the surface;

 (4) neighbouring objects should be at least four diameters away from the gap—to reduce effects due to induced charges.

When taking sparkover measurements, the temperature and pressure of the air in the immediate vicinity of the gap should be noted and suitable corrections applied. It will usually be found that the necessary correction is very small, as the separate corrections nearly compensate each other.

The effect of humidity as recently studied by Whitehead and Castellain is to cause a small decrease in sparkover voltage, due probably to the formation of thin moisture films on the electrodes. Opinions differ somewhat as to the degree of accuracy attainable. If all possible precautions are taken, the error involved in taking the mean of half a dozen readings should certainly be not greater than 1 per cent., and even for rough work it should be within 2–3 per cent. This order of accuracy is exceptionally good, considering how irregular and uncontrollable sparkover tends to be. The instrument is simple, inexpensive, easily portable and handled; however, it should be remembered that the results do not give any idea as to the type of voltage wave beyond its crest value.

The high voltage form of **electrostatic voltmeter** is based on the same principle as that for low voltages—either repulsion or attraction due to charge of like or opposite sign, and it measures R.M.S. voltage values. It usually consists of a fixed and movable system, whose

⊗ Experimental points
by authors.
⊗ Calibrations made on basis of BTH
expts accepted by I.E.C. provisionally.
+ Calibrations put
forward by A.I.E.E. 1927
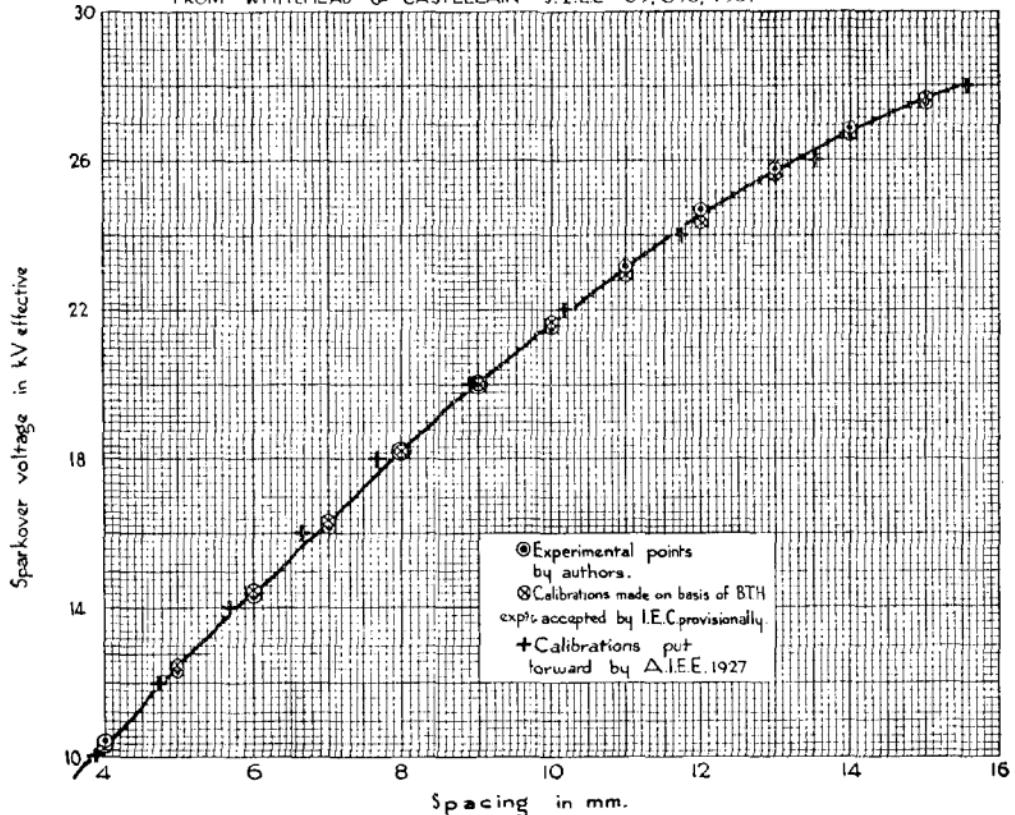
Fig. 7.—Sparkover voltages for 20 mm. diameter spheres.

distance of separation gives an index of the P.D. between them. As the attractive force varies as the square of the voltage, the scale is crowded for the lower voltage values and evens out later on. In the attracted disc type, the attracted disc is connected to the pointer, which registers when the moving disc approaches or recedes from the fixed disc. A slight modification of this is found in the vane type, in which a vane carrying the pointer is attracted between two quadrants after the fashion of the quadrant electrometer. The torsion type is the most common of repulsion instruments, and depends for its action on the torsion of a fibre carrying two movable balls. These, being charged to the same potential as the two fixed balls, are repelled from the latter. This instrument is capable of giving great sensitivity, especially when using a mirror and scale to take readings. The damping is usually obtained, making use of the viscosity effect in oil.

One of the handiest types of repulsion instrument is the Braun electrostatic voltmeter, having a capacity of only 30 $\mu\mu$F, and capable of measuring up to 10 KV. (R.M.S.).

Generally, precision measurements can be carried out up to voltages of about 150 KV. with an error of less than 1 per cent. in most cases. An accuracy of 1/10 per cent. has been achieved by Thornton, who introduced a small metallic ellipsoid about 4 cms. long and about 0·6 cm. diam., into a uniform electrostatic field (between two plates 140 cms. diam., spaced 100 cms. apart) and observed its period of free swing with and without the field. The voltage between the plates is then given by $F = Kn$ volts/cm. where K is a factor which depends on the dimensions of the ellipsoid, and n is the number of swings per sec. of the ellipsoid, with the field applied. This method is indeed elegant, and very little uncertainty attaches to the calculations and observations which have to be made.

The **condenser potential divider** method is based on the distribution of voltage on the two condensers in series

forming the potential divider inversely as their capacity. Thus, if voltage V is applied to two condensers of capacities C_1 and C_2 in series (C_1 being the high voltage small capacity condenser), the voltage V_2 on C_2, as read by an electrostatic voltmeter, is $\dfrac{C_1 V}{C_1 + C_2}$; thus, knowing C_1, C_2 and V_2, the voltage V is obtained. Care should be taken to see that the charge on C_1 at voltage V_1 does not distribute itself over C_2 (through the voltage source), otherwise the voltmeter V_2 will register an additional voltage $\dfrac{C_1 V_1}{C_1 + C_2}$. Davis, Bowdler and Standring have made a thorough investigation of this method, as well as that obtained by rectification of the **charging current of a condenser** as shown. If a sine wave of peak voltage V be applied across C, then one rectifier conducts during the positive half cycle and the other conducts during the negative half cycle and the total charge passed per cycle is 2CV; hence, a current-measuring instrument placed as shown will record a mean current i of $2f$CV, where f = frequency of alternation.

Fig. 8.

Thus, knowing f, C, i, V can be obtained.

For accurate results the impedance of the rectifiers should be very small compared with that of the condenser C, and the wave-shape should be truly symmetrical and without more than one peak in each half cycle.

This measurement can be carried out without rectification if a resistance R of about 100,000 ohms be placed in series with the condenser, and the voltage V′ across this resistance measured by an electrostatic voltmeter. The current through the circuit is then $\dfrac{V'}{R} = 2\pi f$CV, thus giving V.
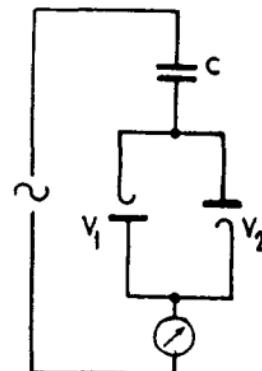
The accuracy claimed for these methods is about 1 or 2 parts in 1000, even for voltages as high as 10^6 volts.

The introduction of the **corona voltmeter** by Whitehead and Isshiki has promised high precision measurements of high voltage. Essentially, the instrument consists of two concentric cylinders between which the voltage is applied. At a certain field gradient $g = A\delta\left(1 + \dfrac{B}{\sqrt{\delta r}}\right)$ at the inner cylinder, where $\delta = \dfrac{3\cdot92 \text{ press.}}{273 + \text{temp.}}$, $r =$ radius of inner cylinder, A and B are constants, corona discharge begins to form there, and is detected either visually, aurally, or by ionization produced—all methods of detection giving much the same accuracy. It is thus clear that by varying δ, the air density, the corona voltage can be made to vary for any particular electrode dimensions. In their instrument, which measured voltages up to 150 KV. peak (at 2 atmospheres pressure), the corona voltage could be detected to within 1/10 per cent., the overall accuracy in voltage measurement being about 0·5 per cent. The diameter of the outer cylinder was 22 ins., and that for the inner cylinder, which was of tool steel, polished and nickel plated, ranged between 1 and 12 mm. The instrument was calibrated from readings of the charging current into a high voltage condenser, as previously described, and was found to give constant results over long periods of time, which did not much alter the surface of the corona electrode. Brooks and Defandorf, at the Bureau of Standards, have further investigated the possibilities of the instrument to 180 KV. peak, and and have given the more accurate expression for the corona gradient $g = A\delta + B\sqrt{\dfrac{\delta}{r}} - \dfrac{c}{r}$, but without taking into account any space charge effect which may be present. They found that increase in humidity lowered the corona voltage for a dusty or soiled inner electrode, but increased it if clean. The instrument, in addition to giving good repeatability, consuming little power and

being independent of its surroundings, gave a maximum error of 1 per cent., and with care this could be cut down to 0·2 per cent.

As a laboratory standard, the instrument holds much promise if developed.

The **ionic wind** voltmeter, as developed by Thornton, Waters and Thompson, is an ingenious application of the properties of the " electric wind " in the neighbourhood of a hot wire which forms the earth side of the H.T. supply.

The application of the field to the wire immersed in some gas such as nitrogen, or carbon dioxide, results in the movement of charged ions away from the wire, thus cooling it, the extent of this forced cooling being proportional to the applied field. The instrument only begins to work above a certain value of applied voltage defined by the instant at which ionization by collision sets in. This limiting voltage can be fairly well controlled, as it depends on the temperature of the wire, the nature of the surrounding gas and its pressure. By making the hot wire part of an ordinary bridge circuit, the out-of-balance reading gives an indication of the applied voltage. The authors, in a very elaborate investigation of influencing factors, have obtained peak values as well as mean values of voltage. This was done by introducing an adjustable earthed guard ring round the hot wire, forming an electro-static shunt, and calibrating against a sphere gap.

The outstanding advantages of the instrument are that it can be used far away from the high-tension source with an accuracy to within 3 per cent., is not influenced by transient surges, and gives constant readings. Its disadvantages, which are not serious in this case, are that the calibration is not independent of frequency or of wave-form of the voltage.

It has been constructed to read up to 300 KV. for indoor use, and as a portable instrument reading from 3–150 KV. for general testing.

CHAPTER II

ELECTRIC FIELDS

WHEREVER a difference of electric potential exists between two points, an electric field exists between them, whose value is defined by the applied potential, form of electrodes, their distance apart, and the medium or mediums in which they are situated.

The whole field can arbitrarily be mapped out, using the notion of Faraday tubes, the number of tubes of force passing through unit area in the field being a measure of its intensity. The lines of force are considered as having their origin on the positive electrode and end on the negative electrode, and, as these are equipotential surfaces, the lines of force must be perpendicular to each; each positive and negative unit of charge constituting a unit tube of force. This conception of the electric field is simple and elegant, and is particularly useful when considering the breakdown of matter which is subjected to electric stress.

The gradient in the field, which determines the electrical stress in unit length, is defined by the equation $g = \mathrm{L}t \cdot \dfrac{\delta \mathrm{V}}{\delta x}$, where $\delta \mathrm{V}$ is the voltage impressed across a length δx. It is obvious that g may not be constant throughout the field, in which case the field is non-uniform. This case often occurs in practice where combinations of dielectrics occur. Usually it is the aim in design to obtain as simple and homogeneous a field as possible, so that all likely stresses may be calculable and known.

This is usually achieved by the use of standard electrode forms, some of which are now considered.

Electrode Forms.—With **parallel plate** electrodes, as in the attracted disc type of electrostatic voltmeter, the lines of force are straight lines normal to the surface of each electrode. The gradient in the field is $\dfrac{V}{d}$ volts/cm. and is constant throughout (edge effects being neglected).

In the case of **coaxial cylinders** the lines of force are radial straight lines from the inner to the outer cylinder (again neglecting edge effects).

The gradient at any point distant x from the axis of the cylinders is $g = \dfrac{V}{x \log_e \dfrac{R}{r}}$ volts/cm.,

where

R = radius of outer cylinder in cms.,
r = radius of inner cylinder in cms.

At the surface of the inner cylinder $x = r$, then

$$g = \frac{V}{r \log_e \dfrac{R}{r}} \text{ volts/cm.,}$$

and this is the maximum gradient between the cylinders.

By differentiation of this expression,

$$\frac{dg}{dr} = \frac{V\left\{\log_e \dfrac{R}{r} - 1\right\}}{\left(r \log \dfrac{R}{r}\right)^2},$$

therefore, in order that g at the surface of the inner cylinder should be minimum, $\dfrac{dg}{dr} = 0$, $\therefore \log_e \dfrac{R}{r} = 1$, $\therefore R = 2.718r$, hence $R = 2.718r$ gives the arrangement for which the gradient at the surface of the inner cylinder has its lowest value ; consequently, this arrangement above all others will theoretically withstand the maximum voltage across it before it breaks down.

2

The lines of force between **concentric spheres** are radial, and the gradient at any distance x from the centre of the system is given by $g = \dfrac{VrR}{(R - r)x^2}.$ As before, the maximum stress occurs for $x = r$, the gradient at the surface of the inner sphere being $\dfrac{VR}{(R - r)r}.$

Since $\qquad V = \dfrac{g(R - r)r}{R} \quad \therefore \dfrac{dV}{dr} = \dfrac{g(R - 2r)}{R}$

if R is constant.

For minimum, $\dfrac{dV}{dr} = 0, \therefore R = 2r, \therefore V = \dfrac{gr}{2}.$ Hence

the maximum breakdown voltage across this system is obtained when the radius of the larger sphere is double that of the smaller sphere.

The field at the point in the case of the **point and plane** electrode system is given by

$$g = \frac{2V}{r \log_e \dfrac{2d}{r}} \text{ volts/cm.,}$$

where

$r = $ radius of the point,
$d = $ distance between point and plane.
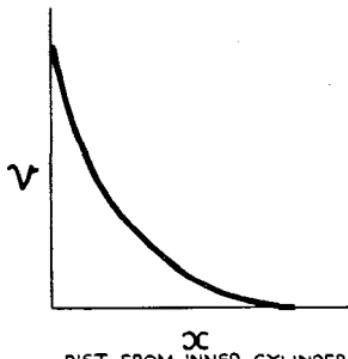
DIST. FROM INNER CYLINDER
FIG. 9.—Voltage distribution (concentric cylinders).

This formula is very useful when calculating field gradients for auto-electronic currents obtained from cold wires in intense fields, and will be referred to later.

In the case of two **equal parallel cylinders,** where the distance of separation d is very much greater than the radius of the cylinder, the gradient g at the surface $= \dfrac{V}{2r \log_e \dfrac{d}{r}}.$ It is thus clear that with this

arrangement, the breakdown voltage is twice that obtained when the cylinders are coaxial and the field balanced (for the same distance of separation and radius r of inner cylinder). When the electrode system is long, as for instance, in the case of transmission lines, the gradient $g = \dfrac{V}{r \log_e d/r}$. By applying the method of mirror images to the case of a short cylinder parallel to a plane at a distance d, the required gradient will be equal to one-half that for two parallel cylinders spaced $2d$ apart and calculated as above.

Combinations of Dielectrics.—The case of a combination of dielectrics placed in parallel is one which is frequently met with in practice, and once the underlying theory is understood, problems in design are much simplified.

Assuming the ideal case in which the boundary between the two dielectrics coincides with a line of force, then, the gradient in each di-

Dielectrics in parallel.
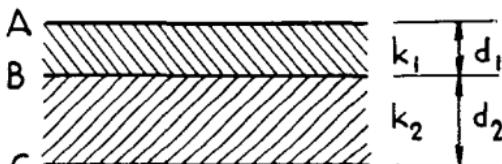
Dielectrics in series.
FIG. 10.

electric is $\dfrac{V}{d}$, and each behaves under the electric stress independently of the other. Either may break down separately, or there may be breakdown at the interface, depending on the value of the gradient there.

When the dielectrics are in series, the combination can be considered as equivalent to two condensers in series, with the boundary as the common plate.

For a given impressed voltage V, these condensers take voltages v_1 and v_2 which are inversely proportional

to their capacities. Thus,

$$C_{AB} = \frac{k_1 \cdot area}{4\pi d_1} \; ; \; C_{BC} = \frac{k_2 \cdot area}{4\pi d_2},$$

where k_1 and k_2 are the dielectric constants of the respective mediums,

$$\therefore \frac{v_{AB}}{v_{BC}} = \frac{C_{BC}}{C_{AB}} = \frac{k_2 d_1}{k_1 d_2}.$$

Taking the simple case where $d_1 = d_2$,

$$\frac{v_{AB}}{v_{BC}} = \frac{k_2}{k_1}.$$

If $k_2 > k_1 \; ; \; v_{AB} > v_{BC},$

$$\therefore \text{ gradient in AB} > \text{gradient in BC} ;$$

hence, because of the unequal gradients, great care is necessary in selecting the insulation, otherwise it is possible for one of the dielectrics to break down at a voltage lower than expected. In doing so, the full voltage will then be transferred to the other dielectric— the gradient in it will increase, and it, too, may break down, owing to the increased gradient.

CHAPTER III

HIGH VOLTAGE ELECTRONS

Electron Waves.—The conception of the electron as possessing properties either as a particle, or as associated with a train of waves whose wave-length is determined by its momentum, was introduced by De Broglie. He followed the rather singular position which prevails in optical theory to-day, where, for example, photoelectric effects require the particle theory, while diffraction is explained on the wave theory.

The fact that electrons of diameter 10^{-13} cms. impinging on a metallic surface containing atom diameters of 10^{-8} cms. give regular reflection, in addition to diffuse reflection, demonstrates their wave nature. This is further supported by the refraction effects obtained with the beams regularly reflected from the metal.

The classical experiments of Davisson and Germer showed that electrons were diffracted by nickel crystals, the atoms of which acted as scattering centres for the electron waves. The cathode ray diffraction experiments of G. P. Thomson further strengthened the wave conception nature of the electron under certain circumstances.

The electron wave-length $\lambda = \dfrac{h}{mv}$, where h is Planck's constant, and m and v are mass and velocity of electron. Hence $\lambda = \sqrt{\dfrac{150}{V}} \cdot 10^{-8}$ cms., where V = potential dif-

ference in volts.   With the relativity correction for mass
$\lambda = \sqrt{\dfrac{150}{V}}(1 - 4\cdot9 \times 10^{-7}V)$, the velocity v (cms./sec.)
being given by $v = 10^7\sqrt{35\cdot38V}$.   Thus 100 KV. elec-
trons have a velocity of $1\cdot8 \times 10^{10}$ cms./sec., and a
wave-length of $0\cdot037 \times 10^{-8}$ cms., i.e. of the same order
as X-ray wave-lengths.   Indeed, as with X-rays, elec-
trons are specularly reflected from a crystal face when
Bragg's law $n\lambda = 2d \sin \theta$ is fulfilled (θ = angle of inci-
dence and d = distance between parallel surface atom
planes), though general scattering is expected.   The re-
flection is selective for the various values of λ, given by
the speed of the electrons which satisfy this equation.

The De Broglie conception can be applied to atoms,
molecules or ions, as well as to electrons.   Johnson got
regular reflection of hydrogen atoms from rock-salt, while
Stern observed diffraction effects up to angles of 35 degrees
when homogeneous helium atoms impinged on lithium
fluoride : the space-lattice pattern values agreed with
those obtained by X-ray analysis.

G. P. Thomson first observed electron diffraction
effects, using celluloid films 3×10^{-6} cms. thick, and
normally ncident 4–16·5 KV. cathode rays.   These
suffered no velocity loss or multiple scattering because
of the thinness of the film.   The photographic pattern
was of the Hull-Debye-Scherrer type for an agglomeration
of crystals oriented at random, consisting of a central
spot surrounded by concentric rings, each of which
corresponds to some plane spacing.   These effects were
verified for single crystals and thin films of polycrystal-
line metals by Read, Ironside, Taylor Jones, Ponte and
Kikuchi among others, using cathode rays of 10–80 KV.
with equivalent wave-lengths of 0·12–0·04 Å.   The latter,
working with mica of 10^{-4}–10^{-5} mm. thickness, got three
interesting types of diffraction patterns, distinguished
as follows :—

    (1) N pattern ; net like and due to diffraction by a
        two-dimensional lattice.

(2) L pattern ; giving spots as in Laue's case and due to a three-dimensional lattice.

(3) P pattern ; consisting of pairs of black-and-white lines due to multiple scattering and selective reflection.

The diameter D of any diffraction ring varies directly as λ, i.e. as $\dfrac{1}{\sqrt{V}}$, hence $D\sqrt{V}$ should be constant ; this is shown by Thomson's table (from *P.R.S.* 125, p. 356) :—

V(KV.).	D(cms.).	$\dfrac{D\sqrt{P}}{(1+Pe/1200\,mc^2)}$.
15·8	1·53	194
23·3	1·28	198
27·3	1·18	198
34·5	1·06	200·5
42	0·96	201

Factor in brackets is the relativity correction and does not exceed 2 per cent.

The consecutive ring diameters allow the determination of crystal atomic arrangements as well as the distance between crystal planes.

The electron intensities in the rings, and the relative number of electrons in rings and central spot for 10^{-6} cm. thick gold films with 20–48 KV. electrons is discussed by White. Using a photographic method, he obtains the number of electrons per unit area at various distances from the central maximum, by assuming the reciprocity law to hold, i.e. exposure time for given blackening varies inversely as electron intensity. A normal Gaussian error curve $y = y_0 e^{-x^2/a^2}$ was obtained where " x " is the distance from the central ordinate (within 2 mm.), and " a " a constant depending on voltage and photographic film density. The electrons which made up the central spot suffered no scattering whatever—they passed

straight through the film : background electrons suffered multiple scattering, while the ratio of the number of electrons in rings, central maximum and background was approximately 1 : 8 : 40.

Diffraction phenomena have successfully elucidated surface structures and surface phenomena, because the electron penetration is small.   Thus 10 KV. electrons are completely stopped after passing through a distance of 1000 Å. in aluminium ; even 35 KV. electrons only go $1·2 \times 10^{-7}$ cms., hence surface layers up to tens of molecules thick give good diffraction effects.

The fact that electron waves tend to show a polarization effect, brings back the particle idea once more, since on the modified Dirac theory, which includes electron spin, the polarization effect will be selective, if the scattering is selective, i.e. if the number of electrons scattered in any particular direction depends on the previous orientation of their spin axes.   Thus, starting with a normal beam containing a random distribution in direction of the spin axes, a first scattering will result in an asymmetric scattered intensity, because the act of scattering causes more spin axes to point in one direction than in another.   This means that the beam is partly polarized, so that double scattering experiments should show the disymmetry in the first scattered beam.

In these experiments the secondary scattered intensity should, if a polarization effect is present, be a maximum when the planes of incidence of both scatterings are parallel, and a minimum when they are perpendicular.

The theoretical work of Mott on these lines shows that the following three conditions are necessary to give an observable effect : (1) electron velocity must be high, (2) both scattering angles must be large, (3) the scattering nuclei must have high atomic number.   Besides experimental difficulties, some idea of the magnitude of the effect can be got from the fact that with gold leaf 10^{-5} cm. thick and 100 KV. electrons, the intensity of a beam twice scattered at 90 degrees is only 10^{-12} of its initial value.

On the whole, the results obtained while generally positive, and showing a small effect, are none too conclusive. Low voltage (up to 100 volts) electrons give no effect. Rupp has indicated as much as 12 per cent. asymmetry for 80 KV. electrons scattered twice at grazing incidence from gold, and later got large asymmetry in his diffraction pattern, using 220 KV. electrons scattered at 90 degrees, first from a thick gold target and then diffracted by thin gold foil. However, Langsroth, working with 10 KV. electrons, scattered twice at 90 degrees from thick tungsten targets, got less than 1 per cent. asymmetry, while Dymond, using 70 KV. electrons, scattered twice from gold foils, got only 2 per cent. asymmetry.

Further analogy between electron waves produced by electrons of constant velocity and light waves is furnished by the fact that electron beams can be focussed by magnetic and electrostatic fields. These act in much the same way as a lens or prism does towards light waves. A lucid account of various cases met with in practice has been given by Zworykin.

With magnetic focussing, the narrow electron beam travels parallel to the uniform magnetic field (usually produced by current in a coil coaxial with the beam). This acts on any electron making an angle θ with the field, with a force $\text{H}ev = \dfrac{mv^2}{r}$, where v is the radial velocity tending to make the electron take a spiral path of radius $r = \dfrac{vm}{e\text{H}}$ during its course through the field.

The time that the electron spends in the field will of course depend on the length and strength of the field, but the time taken by the electron to traverse one turn of the spiral being $\dfrac{2\pi r}{v} = \dfrac{2\pi m}{e\text{H}}$ thus depends only on the strength H of the field, so that no matter what may be the angle θ of inclination of the original electron beam to the field, the magnetic field will focus all the original

point sources to the same point. Such a method of uniform magnetic field focussing was used by Bush in his $\frac{e}{m}$ determination.

The case of electrostatic focussing is more interesting, and has been extensively employed to deflect electron beams. In practice, the electrostatic field is produced between two or more electrodes, the more common forms consisting of concentric cylinders or coaxial diaphragms held at different potentials. Here the field acts as if it was a medium of refractive index

$$\mu = \sqrt{1 + \frac{E_F}{E_B}},$$

where E_F = P.D. (volts) of electrostatic field, and E_B = electron energy (volts) of the beam, so that the latter is refracted on entering the field. Any electron within the beam is acted on by the deflecting force of the electrostatic field, as well as by the radial magnetic force due to the current carried by the electrons. This latter force can be shown to be sufficiently small to be neglected
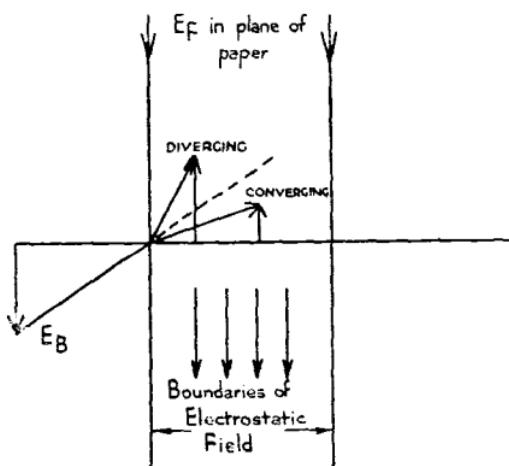
FIG. 11.—Electrostatic focussing.

only at voltages much below 10 KV. It can be seen that, by suitably adjusting the ratio $\frac{E_F}{E_B}$, the index of refraction of the field for the electron beam can be made to be greater or smaller than unity.

When $E_F > E_B$, i.e. with an accelerating field, $\mu > 1$

and the field acts as an electric lens, focussing the electrons, so as to produce a converging beam.

When $E_F < E_B$, the electric lens produces a diverging beam, as shown.

High Voltage Cathode Rays.—Progress in the production of high voltage cathode rays has followed the lines of development of high vacuum technique. Lenard's original rays had a range of 8 cms. in air ; up to the present, Coolidge has produced cathode rays of 250 KV. and more, and having a range of some 50 cms. in air.

The cathode is an incandescent tungsten spiral, and the anodes have various forms depending on whether the rays are to be used inside or outside the discharge tube. In the latter case the anode is an aluminium window 0·0254 mm. thick and 3 cms. square, and, with an energy input of 260 watts, reaches a temperature of 340° C. in 10 secs.

A tube of this type, having a thin-walled glass window 2·5 cms. diameter and 0·0005 cm. thick, which will withstand atmospheric pressure, has been described by Slack. The energy loss in the window, depending as it does on its density and thickness, was kept low by having each of these as small as possible. While all the electron energy was absorbed in the window at 20 KV., only $\frac{3}{4}$ per cent was so absorbed at 200 KV., thus indicating the much greater efficiency to be obtained at higher voltages.

The design of these tubes, and, in fact, all extra high voltage vacuum devices, is very important indeed.

Firstly, the electron stream is magnetically focussed at the anode end ; this determines the size of the focal spot on the anode (window) ; secondly, to prevent overheating the focal spot, the energy distribution should be uniform.

For good results, Coolidge, Dempster and Tanis used thick-walled, mould-blown tubing. To prevent electron reflection and its consequences—build-up of wall charges —a long and narrow anode arm with a hollow anode was best.

The presence of "field currents," i.e. electrons pulled out of the cold cathode by the intense fields at its surface,

proved a difficulty which greatly limited the applied voltage, owing to flow of current in the reverse direction. Proper degassing of the electrodes greatly diminished this effect.

By cascading three tubes, Coolidge has got up to 900 KV. rays. Their range outside the tube is determined, using lime, which fluoresces orange ; and is greatest in the direction in which they are moving. The penetration of 200 KV. rays in air is some 36 cms. in their original direction ; they are scattered 25 cms. in a direction perpendicular to this when passed through 1/1000 in. aluminium ; in nickel foil the range of these same rays is only 0·081 mm.

Their action on matter has been observed in detail by Coolidge and Moore. Diamonds show no colour change after 30 mins. with 200 KV. rays (1 mA.) filtered through 0·0127 mm. nickel, whereas fused quartz turned purple throughout its mass. The blue-white scintillations observed on the surface of rayed calcite were due to discharge between the small areas of built-up surface charges. These were more easily obtained at liquid air temperature, but disappeared at 180 degrees C. due to loss of insulating properties. The bombarded areas, when examined under the microscope, were pitted, the greatest depth of penetration being the maximum range of the particular cathode rays in the substance.

Cathode ray bombardment of some insulators, for example, resin and amber, show that they have the property of retaining charge throughout their volume for long periods of time ; such effects were absent with bakelite and glass. In fact, it would appear that the property of scintillating under the rays at room temperature is a necessary condition for the insulator to acquire this property of depth charge. High voltage electron bombardment of glass persistently occurs in most high voltage high vacuum tubes. Lead glass usually fluoresces blue without leaving any permanent record of the bombardment, whereas soda glass fluoresces green, and prolonged bombardment discolours the

bombarded region to a faint purple. Secondary emission from the bombarded region usually occurs, resulting in the glass acquiring a positive charge ; in some cases if the potential with respect to the cathode acquired by the region is sufficiently high, considerable heat is generated and may warm the glass appreciably.

Coolidge, Dempster and Tanis observed the presence of small yellow spark discharges within the bombarded regions, due to local surface charges. These penetrate some distance into the surface, and produce the large numbers of intersecting canals seen under the microscope.

Where negative charging up of the glasswork occurs, the characteristics of the tube are greatly affected. For example, several thousand volts may be required across an extra high-tension thermionic rectifier to give saturation with a negative charge on the glasswork ; with the glass shielded from the electron charge, this figure may be considerably reduced—in some cases to one-tenth of this value.

Secondary Emission.—Electrons striking a solid obstacle suffer (1) reflection, (2) absorption, (3) transmission, the extent of each depending on their velocity and the kind of matter encountered. Due to the bombardment by this light-fast particle, the matter is as a rule " surface ionized," the ejected electrons having velocities of only a few electron volts. Fröhlich showed mathematically that a lower limiting primary electron energy of 10 volts is necessary in order to get this secondary emission, and, further, that the maximum velocity of the secondary electrons must be less than 25 volts and independent of the speed of the primary beam.

The term " secondary " is used to include both " surface ionized " and reflected primaries. The experimental work of Farnsworth with nickel bombarded by slow electrons up to 260 volts energy showed that for primary electron velocities of from 0·2–9 volts pure reflection at the target takes place, the reflection coefficient being about 1/5. The velocity of these reflected or secondary

electrons found by the retarding field method has corresponding values up to 9 volts. With increasing primary velocity surface ionization sets in and the secondary electrons, distributed in all directions, now consist of both reflected and emitted electrons, the latter all of low velocity, while a small percentage of the former have velocities equal to that of the primary electrons.

The ratio of secondary to primary electrons increases with primary electron velocity up to a certain limit (in this case 260 volts, with a 1 : 1 ratio), and then regularly decreases, the low velocity secondaries being predominantly present at each stage. The magnitude of the ratio greatly depends on the nature of the target surface. Surface contamination by air or hydrogen films, or by electropositive impurities, may increase it three or four times, and alkali films on an oxidized surface even higher than this.

The work of Ahearn with heat-treated tungsten is interesting because of the critical slope changes developed in his curves below 40 volts primary velocity. These may be connected with either the Davisson-Germer diffraction effects, or the photoelectric action of the soft X-radiation produced. Heat treatment of the target eliminated nearly all but the 70 volt critical potential found above 40 volts, indicating surface effects above all others. When the primary electron velocity increases to several KV., an additional type of secondary emission —" rediffusion "—first pointed out by Becker, occurs. Some of the primary electrons are deflected back or " rediffused," with most of their original speed, by short-distance nuclear reactions. This has been supported by Stehberger, who has found this type of emission with gold, lead, copper and aluminium bombarded by 2–10 KV. electrons ; the true secondaries in his case have a velocity less than 36 volts, which is independent of (a) primary electron velocity, (b) the substance being bombarded, (c) its thickness. He further finds the ratio of total secondary to primary to decrease from 3·5 at

1 KV. to about 1 at 9 KV. in the case of platinum foil—the decrease indicated above for slower electrons occurring here as well.

Further confirmation and extension of the above main results comes from the work of Baltruschat and Starke, who examined the secondary emission from aluminium, bismuth, lead, tin, tantalum, platinum, carbon, zinc.

The velocity distribution given by the retarding potential method showed, that for perpendicular incidence the bulk of the true secondary electrons have velocities less than 15 volts at all primary speeds up to 8 KV. (there were 10 per cent. with speeds greater than 3 KV. at 8 KV.).   At higher voltages the number of secondaries with speeds exceeding 3 KV. increases, being 50 per cent. at 12 KV. and 80 per cent. at 30 KV.

Chylinski, working with primary electrons of (5–20) KV. velocity, striking a silver target at 45 degrees, found the maximum secondary electron velocity was as high as 80 per cent. of the primary; indeed, it appears from the scattering experiments of Neher that an appreciable number of high velocity electrons (up to 145 KV.) are scattered without any appreciable energy


Aluminium 40 KV primary rays

THICK

THIN

DENSITY

0·9   0·72
eV₀
KINETIC ENERGY

Fig. 12.

loss, their intensity distribution being given by Rutherford's Cosec⁴ $\theta/2$ law.   To make sure that no secondary electrons interfered with his scattering results, he applied stopping potentials of half the primary electron velocity —a most necessary precaution under the circumstances.

These results agree with Wagner's for cathode rays of (16–40) KV. bombarding targets of silver, gold and aluminium.   He examined the magnetic spectra of the emitted high-speed secondary electrons, using a
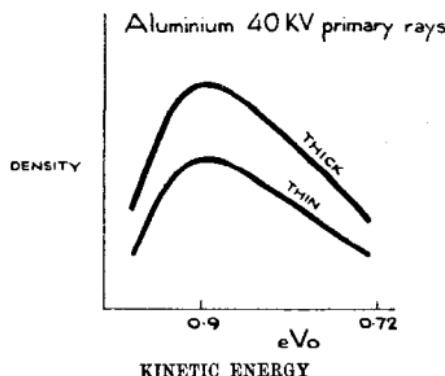
photographic method. As is seen, the velocity spectra are continuous. The maximum secondary velocity indicated with gold and silver was 0·94, and with aluminium 0·85 that of the primary velocity.

He further speculates as to the origin of the secondary electrons, and concludes that some small portion of them come from the inner atomic orbits (L, M, N levels, etc.) of the target. His results with thick and thin targets which give the same spectra lead him to believe that the origin of the bulk of the electrons lies close to the surface—within 0·2μ for gold up to 40 KV., and somewhat greater than 0·5μ for aluminium only above 20 KV.

Absorption and Transmission.—In discussing electron absorption in matter, it is necessary to specify whether the absorption is apparent, i.e. neglects reflected and secondary electrons, or real, i.e. defines the true number of electrons actually absorbed in the material. If I = incident electron current, and i_r, i_a, i_t the reflected, absorbed and transmitted portion of it so that

$$\text{I} = i_r + i_a + i_t,$$

then the apparent absorption, expressed as a fraction, neglecting as it does the reflected electrons, will be given by $1 - \dfrac{i_t}{\text{I}}$, while the real absorption will be $\dfrac{i_a}{\text{I}}$. No fixed general laws for the apparent absorption in various elements have been found, since, for instance with gold, it varies inversely as (velocity)^2 of the rays, while with aluminium it varies inversely as (velocity)^4 of the rays. However, in the case of true absorption, the variation is inversely as (velocity)^4 for all elements. The curves of absorption and thickness resemble somewhat the Bragg α-ray curve for air, and are thus very much alike in shape for all elements. The ionization produced by electrons is, however, only 1/10 that for α-rays of the same speed in air. Extrapolation of the curve to thicknesses where the absorption current becomes equal to the incident current, gives the range of the given electrons in the material. Theoretically, according to J. J. Thomson,

the ionization efficiency of electrons should vary inversely as their energy. Smith, and more recently Liska, found the experimentally obtained values to be somewhat in agreement with theory for high values of the energy, as Liska's table shows. The application of the wave mechanics to the problem by Bethe has given even more successful results.

| KV. | No. pos. charges per electron per cm. path per mm. press. | |
	Helium.	Mercury Vapour.
2·5	0·2150	3·8
6·0	0·0945	1·76
8·0	0·0700	1·28
11·0	0·0520	0·94

Schonland, using cathode rays of (0·2–0·4) velocity of light, investigated the variation of transmitted and absorbed electrons with various velocities. His curves
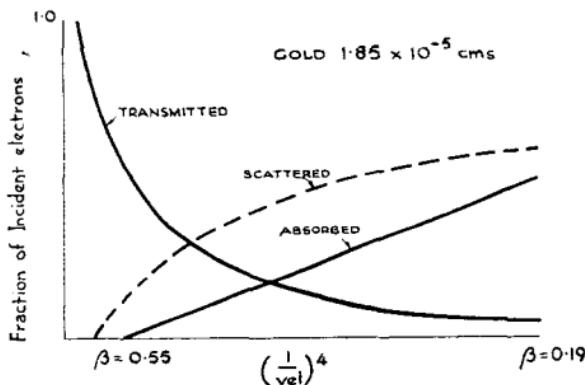

Fig. 13.

show that the fractions absorbed and scattered back each tend to approach 0·5 of the number of incident electrons at low velocities, as they should do. With true absorption in aluminium, copper, silver and gold

3

the product of range (R) and density of the absorber (d), i.e. Rd, was constant, while the product RN (N, atomic number of absorber) decreased with increasing N.

Bohr has shown theoretically that the range in any element should vary as (velocity)[4]. Contrary to Lenard's view that the energy loss in the matter is sudden, and takes place in one single collision, probably with an atomic nucleus, Bohr holds that the energy loss is gradual, taking place over many extra-nuclear electron collisions which obey the classical laws. His assumptions that the energy transfer during electronic collisions is small compared with that necessary to ionize, and that the time involved in the collision process is negligible in comparison with the free period of the electron, allow him to find a limiting value for the energy loss. This is in good agreement with experiment.

The fact that no discontinuities are observed in the absorption curve indicates that the energy loss in single encounters, whether with electrons or atoms, is quite small. In fact, Kramers has shown that increasing the initial electron energy to the point at which it excites the continuous X-radiation of the material, involves radiation energy losses negligibly small compared with the loss due to large numbers of electronic collisions.

Where the electron velocity is extremely high, say from about 100 KV. and upwards, and where the relativity correction is important, Bethe has shown that minimum energy loss of the order 2×10^6 volts/gm./cm^3. in water occurs for electrons of $1 \cdot 5 \times 10^6$ volts ($\equiv 96$ per cent. c), and rises for higher or lower velocities. This is interesting, and shows the complexity of the collision process. Protons in comparison suffer decreasing energy losses with increase in speed of the proton over much the same voltage range.

The transmitted electrons can be analysed by a magnetic field placed at right angles to their motion. Since v cm./sec. $= \dfrac{e}{m}$Hr, the velocity distribution trace can be got as a photograph by varying r and keeping H constant.

The distribution is found to be everywhere continuous, although the intensity, i.e. number of electrons per unit area, is considerably diminished by the effects of absorption in the foil (thickness of order 10^{-5} cms.).

Lenard's first experiments with 30 KV. cathode rays showed that the velocity loss was homogeneous, the transmitted intensity being represented by the usual exponential equation $I_t = I_0 e^{-\lambda t}$, where λ was a constant, depending on the density of the material and velocity of the rays. Whiddington, with (8–20) KV. rays, showed that $\lambda \propto \left(\dfrac{1}{\text{vel.}}\right)^4$ within certain limits, but his results gave an inhomogeneous velocity loss. Terril, working with homogeneous (25–51) KV. cathode rays, penetrating rolled foils of silver, aluminium, gold, beryllium and copper, found a continuous velocity distribution curve for the transmitted electrons. His curve shows that the transmitted rays contain electrons of all velocities almost up to those of the primary rays, and in addition, there is a most frequent velocity (v_f) present (see Fig. 14).

Application of J. J. Thomson's absorption formula $v_0^4 - v_f^4 = ad$, held good in all his cases.

Here v_0 = initial primary velocity cms./sec.,
  v_f = most frequent transmitted velocity, i.e. the velocity corresponding to the greatest intensity transmitted,
  d = thickness of foil,
  a = a constant for the metal, which increases slowly with the primary ray velocity. For aluminium, he got the value $1 \cdot 4 \times 10^{43}$ C.G.S. units, agreeing with Bohr's theoretical $1 \cdot 3 \times 10^{43}$, though other experimenters give somewhat different values.

The formula can, if preferred, be written $V_0^2 - V_f^2 = bd$, where V is now the velocity in equivalent volts and b is a different constant which varies with the density, since the ratio $\dfrac{b}{\rho}$ was constant in all the experiments.

Further confirmation of the continuous velocity distribution of the transmitted electrons, using the magnetic analysis method, has been obtained by Becker (15–50) KV., Miss Allen (2–20) KV., and by Klemperer (4–13) KV., among others. The emerging electrons were certainly less homogeneous than the primary beam, due, of course, to multiple electronic scattering in the foil. The breadth of the velocity distribution increased with the foil thickness and density of the foil, as is to be expected, and also became narrower as the primary beam velocity was increased.
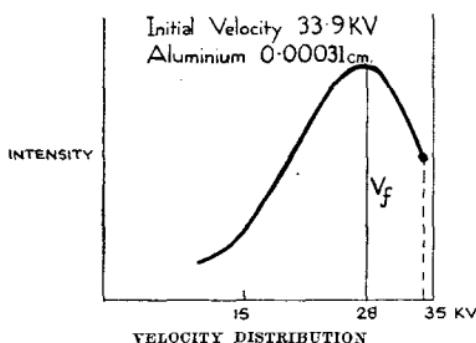
FIG. 14.

The following table, taken from Klemperer's paper, shows how the relation $V_0^2 - V_f^2 = bd$ holds true for aluminium :—

V_0. KV.	V_f. KV.	$V_0^2 - V_f^2$.	Thickness.
6·55	4·3	24·4 ⎫	
8·3	6·6	25·3 ⎬	0·5 μ
10·0	8·6	26 ⎭	
9·65	6·4	52·2 ⎫	
12·10	9·7	52·3 ⎬	1·0 μ

Rather interesting results by White and Millington for the shape of the straggling curve of homogeneous β particles falling on thin sheets of mica (2–6 mgm./cm.^{2}) have confirmed the above type of relation. In general, the velocity distribution found by photometry of the magnetic spectrum of the rays, gave a Gaussian error

curve of the form $y = \dfrac{\beta^3}{\sigma} f\left(\dfrac{\beta^3 x}{\sigma}\right)$, where $\beta = v/c$, $\sigma =$ thickness of foil in centigrams/cm.².

The most probable velocity loss was found to vary approximately linearly with the thickness of mica traversed, while the thicknesses necessary for equal loss varied as (initial velocity)³.

Scattering. — The transmission of electron beams through matter has so far been considered without reference to their direction of emergence.

The attractive force of the nucleus deflects the electrons away from their original path during transit through the atom, but generally they emerge with little change in velocity. On the other hand, in their encounters with electrons in the atom, the collisions now take place between particles of similar mass, resulting in both change of direction and velocity.

The original Rutherford atom model predicted that the fraction of the original beam scattered through an angle greater than θ was $\pi n t \dfrac{e_1^2 e_2^2}{4\mathrm{T}^2} \cot^2 \theta/2$,

where $n =$ number atoms per unit volume,
           $t =$ thickness of material,
           $e_1 =$ charge on the nucleus,
           $e_2 =$ charge on the particle,
           $\mathrm{T} =$ energy of the particle.

This prediction was well verified by Chadwick for α particle scattering by silver, gold, and copper foil. Further, he showed that the nuclear charge could be given to an accuracy of 1 per cent. by the value of Ne, where N $=$ atomic number and $e =$ elementary electron charge.

Further application by Rutherford to the case of β-ray scattering showed, that within certain limits, the formula could be successfully applied; indeed, the experimental results of Chadwick and Mercier, using β-rays from radium E, verified the single scattering law. Two important factors have, however, to be further considered.

These are (1) change of mass with velocity of the particle, slowing it down during transit, with consequently greater time for reaction, (2) applicability of the inverse square law (assumed in deducing the formula) when the distance of approach to the nucleus becomes comparable with the wave-length of the particle.

Thus, in the case of small angle scattering of β-rays by light elements, such as carbon and aluminium, Schonland's values are nearly double the theoretical values, but with heavy elements, such as gold and platinum, the calculated and observed values agree closely.

Calculation showed, further, that the distance of approach to the nucleus was smaller for light elements than for heavy elements, being $6 \cdot 5 \times 10^{-11}$ cms. and $2 \cdot 5 \times 10^{-10}$ cms. for aluminium and gold respectively.

The experimental difficulties and uncertainty as to the type of scattering have to a large extent been diminished by using high voltage cathode rays, where the intensity and homogeneity of the bundle can be varied within wide limits. In the case of cathode rays, however, a further consideration must be taken into account which does not enter when dealing with β-rays. This is the radiation of energy due to cathode rays in looped or spiral orbits round the nucleus, when they come within a certain critical distance of it, given by Darwin as

$$\frac{Ne^2\sqrt{1 - \beta^2}}{m_0 c^2 \beta},$$

where Ne = nuclear charge, $\beta = v/c$.

The effect of neglecting this unknown radiation of energy term is to give experimentally increased values for the amount of scattering—increases which can be quite considerable, when, as with aluminium, the cathode ray passes within three times of this critical distance from the nucleus. The relativity correction (1) already referred to, has been worked out by Schonland, who showed that the original Rutherford formula had to be multiplied by a function of angle and velocity before it explained his results. He thus gives the fraction ρ of

the original beam scattered between the angles ϕ_1 and ϕ_2:

$$\rho = \pi/4 \,.\, nt\left(\frac{Ne^2}{T}\right)^2\left[\cot^2\frac{\phi_1}{2}f^2(\phi_1, \beta) - \cot^2\frac{\phi_2}{2}f^2(\phi_2, \beta)\right].$$

The theoretical value for ρ agreed to within 2 per cent. with the observed value and the relations between (ρ, t), (ρ, N^2), $\left(\rho, \dfrac{1}{T^2}\right)$ were also found to agree with the formula for silver, aluminium and copper up to 70 KV.

Without this relativity correction, the Rutherford formula gives a value for ρ which is only some 40 per cent. of the experimental value. Incidentally, the $\left(\rho, \dfrac{1}{T^2}\right)$ relation verifies that the inverse square law was a valid assumption, at least in the cases considered. The curves for ρ and t were only partly linear—the scattering ratio increasing rapidly after a certain thickness for each energy of rays. This indicates the existence of plural scattering.

Wentzel has shown theoretically that a criterion for single scattering is obtained if the angle of scattering is some small multiple of the minimum deflection δ, at a distance $R = \sqrt{\dfrac{2}{\pi nt}}$ from the nucleus. The value of δ is got from $\cot \delta/2 = \dfrac{2T}{Ne^2}\sqrt{\dfrac{2}{\pi nt}}$.

In Schonland's experiments $\dfrac{\phi}{\delta}$ was greater than 3 for all his foils; he thus worked under conditions giving single scattering. Neher, in some further work on these lines, shows that Wentzel's criterion for single scattering is not sufficiently well defined, for the ratio appears to increase with the energy of the cathode rays, being 3·3 at 45 KV. and 6·1 at 145 KV. for aluminium. He puts forward a more critical test by which single scattering may be judged to have taken place—if the curve connecting ρ and ϕ does not change shape with increasing energy of the primary rays. Mott, in a mathematical investigation

into the scattering of fast electrons by atomic nuclei, uses the wave equation of Dirac and includes both the effects of relativity and spin—the direction of the latter does affect the intensity of scattering. The unknown effects due to radiation do not come in, since the wave-lengths dealt with are large compared with the critical distance of approach. The magnitude of the spin term becomes comparable with that of the inverse square law deflecting force, when the electron has an equivalent velocity of 40 KV. and over.

The fraction ρ of the beam scattered between the angles ϕ_1 and ϕ_2 was

$$\rho = \frac{\pi n t N^2 e^4}{m c^4}\Big(\frac{1 - \beta^2}{\beta^4}\Big)$$
$$\Big[\cot^2\frac{\phi_1}{2} - \cot^2\frac{\phi_2}{2} - 2\beta^2 \log \sin \frac{\phi_2/2}{\sin \phi_1/2}$$
$$+ \frac{2\pi\beta N}{137}\Big(\sin\frac{\phi_1}{2} + \operatorname{cosec}\frac{\phi_1}{2} - \sin\frac{\phi_2}{2} - \operatorname{cosec}\frac{\phi_2}{2}\Big) + \dots\Big].$$

This equation differs somewhat from the Schonland modification to Rutherford's original α-ray scattering equation, but the results obtained by Neher with cathode rays of 56–145 KV. energy have confirmed some of the relations which it predicts.

For instance, the relation between ρ and energy of the beam, in the case of aluminium between the angles 95° 10′ and 172° 5′ agrees with the above formula, as well as the dependence of ρ on angle of scattering. However, the ratio $\dfrac{\rho}{n t N^2 f(\phi/2)}$ was not constant for all elements as predicted on other theories, but increased with N as it should do on Mott's theory, but the agreement here was not good.

The greatest discrepancy between theory and experiment arises in deducing the absolute value of ρ. In Neher's case with aluminium it was 1·32 times Mott's theoretical value and from 0·5–0·66 that of Schonland. The difference may possibly be due to the effects of

secondary electrons. These in Schonland's case should not be overlooked, since his stopping potentials were only about 200 volts, although, as previously stated, an appreciable fraction of secondary electrons with energies up to half the primary energy are undoubtedly liberated by surface bombardment.

Allen has shown that where multiple scattering occurs, as with small angles of scattering, the fraction scattered with any given velocity is a Gaussian error function
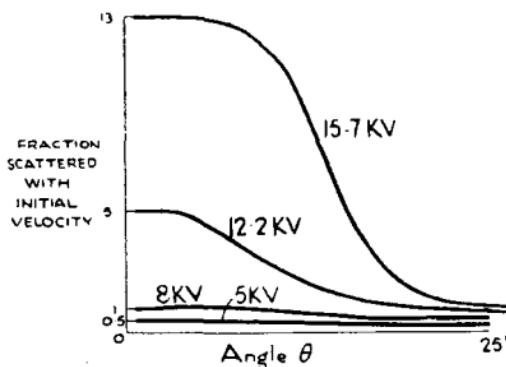

FIG. 15.—Multiple scattering.

of the angle of scattering, being given by the curve $y = y_0 e^{-\varphi^2/2\lambda^2}$, where ϕ = angle of scattering and λ is a constant, which, according to classical scattering theory varies inversely as (electron velocity)^2.

A previous mathematical investigation by Bothe of small angle (multiple) scattering showed that this type of law agreed with the experimentally obtained direction distribution, and, further, that the calculated values of absorption coefficients in aluminium for various ray energies agreed with the experimentally obtained values.

CHAPTER IV

HIGH VOLTAGE POSITIVE IONS

Sources and Circuits.—The discovery by Kunsman, Harnwell and Barton that singly charged positive ions of Na, K, Rb, Cs, Mg, Ca, Ba, Sr are emitted by a fused mixture of iron oxide, and a small percentage of any of the above elements when heated has furnished a ready source for positive ion investigations. Reduction in hydrogen and thorough outgassing gave constant positive ion currents which obeyed the usual Richardson equation. Constant currents of 4×10^{-4} amps./cm.^{2} have been obtained for 40 hours continuously, using the systems of alkali aluminium silicates $3Li_2O\ Al_2O_3\ 3SiO_2$ for Li ions, and $3K_2O\ Al_2O_3\ 3SiO_2$ for K ions. Where protons or gas ions of any type are required, an auxiliary discharge tube or hot cathode arc with a hole in the cathode is used. The positive gas ion then passes through the hole and is further accelerated.

Any of the high voltage circuits previously described can be used for accelerating the positive ions, but special circuits have been satisfactorily developed for work much above 500 KV. for nuclear investigations.

The Tesla coil previously described has been used for this work up to 3×10^6 volts, but, owing to the extremely short on-time of the voltage, very intense positive ion sources are necessary for consistent results. Two circuits in particular, those of Cockcroft and Walton and Sloan and Lawrence respectively, have been used with much success in the earlier investigations on nuclear

structure. In the former, the transformer T charges condenser C_3 to potential E through the continuously evacuated high voltage thermionic rectifier V_1 when T is positive. When T is negative, the condensers C_2 and C_3 are then in series through V_2 so that C_2 shares part of the charge on C_3. On the next half cycle C_2 shares part of its charge with C_4 through V_3, V_1, and when this process is repeated many times, the condensers C_1, C_2, etc., are each charged to potential E, so that a voltage nE is available, where n = number of condensers used.

To get full multiplication and a voltage fluctuation of less than 2 per cent. it is important for the rectifier emissions to be at least thirty times the load current, because the charging period is only a small fraction of the cycle.

The authors during their work discovered that plasticine covered with low vapour pressure grease made good vacuum-tight joints.

The method originated by Ising for the multiple acceleration of ions is rather ingenious. It was developed by Sloan and Lawrence with much success. The ion energy is stepped up by making the ions pass through a series of metal coaxial accelerator tubes in vacuo, and so arranged that

FIG. 16.—Cockcroft and Walton circuit.

the field is always in the same direction, as the ion passes from tube to tube. This is achieved by connecting alternate tubes together, and applying the H.F. voltage from an oscillator to the two terminals as shown. Currents of 10^{-7} amps. of singly charged mercury ions of $1 \cdot 26 \times 10^6$ volts have been obtained in this way, using an H.F. voltage of 42 KV. at

30 metres, applied to thirty such copper tubes 5 mm. diameter, the overall length being only 114 cms. The accelerators are made longer and longer to allow for the increased speed of the ion, as it passes up the system. The authors visualize the extension of the method to produce 10^7-volt singly charged mercury ions, using a system of accelerators 40 ft. long, fed by eight power amplifiers in parallel.

Fig. 17.—Sloan and Lawrence circuit.

Ionization.—Owing to the complex structure of the positive ion, as compared with the electron, ionization effects are on the whole more difficult to interpret. That ionization by positive ions occurs above about 200 volts has been established by Sutton and Mouzon, working with K^+ in purified helium at pressures of $1/100 - 1/10$ mm. Hg. They found that argon gave the largest number of electrons per positive ion per cm. path per mm. pressure (6, at 800 v.). Mouzon, working with the alkali ions in the rare gases up to 2 KV., verified these results. The probability of ionization P, expressed as the product NL, where N = number of electrons liberated per positive ion per cm. path per mm. pressure, and L = kinetic theory value of the M.F.P. at 1 mm. pressure, is quite small. For example, at 500 volts, P has a value of about 0·026 for K^+ in argon. There was a definite tendency for N to reach a saturation value roughly between 5 and 10 in most cases at voltages in the neighbourhood of 2 KV.

Gurney, working with 7 KV. K^+ ions in hydrogen could get no ionization at pressures of $1·7 \times 10^{-3}$ mm., and concludes that if it exists at all, the ionizing efficiency of the positive ion is less than 1/150 of that of 50-volt electrons. This means that the M.F.P. of the positive ions must be of the order of tens of times that

of the kinetic theory value. However, some recent work by Frische, using K^+ in A, Ne, He, N_2, CO, H_2, Hg, tends to show that the efficiency of ionization by positive ions is at least comparable with that by electrons, since the maximum numbers of ions/ion/cm./mm. pressure in argon were 8·5 and 10 respectively for respective voltages of 4 KV. and 150 v.

The minimum voltage for ionization by K^+ varied from 100 volts for A to 1600 volts for hydrogen, the curves for argon and neon showing saturation at about 4 KV. at 8 and 2 ions/ion/cm./mm. pressure respectively.

With lighter ions, protons and H_2^+ for example, Dempster found little energy loss, and hence no deflection or neutralization ($< \frac{1}{2}$ volt per collision) for 900-volt ions passing through helium.

Goldman, working with protons up to 4 KV., striking H_2 or A, got no certain ionization. At higher voltages, up to 40 KV., Verwiebe got definite evidence of ionization of the residual gas by hydrogen molecular rays while investigating the radiations emitted by impact on a metal target. At 10^{-4} mm. Hg the radiation excited had a wave-length of λ 1216 A° (the first Lyman line).

Very interesting results have been obtained by Rudnick on the M.F.P. for capture and loss of electrons (L_1 and L_0 respectively) by He^+ ions of 5–21 KV. energy (approx. $0·5 - 1 \times 10^8$ cms./sec.), passing through helium. He finds L_1 to be about 10^{-4} cms. (at 760 mm.), and to be independent of the speed of the impinging ion, while L_0 varied from 40×10^{-4} cms. at 5 KV. to $8·6 \times 10^{-4}$ cms. at 21 KV., i.e. approximately inversely as (velocity)^2. Incidentally, he found that 80–90 per cent. of the atoms in the beam are neutrals in the equilibrium state ; the ionizing power of the neutral He atom was very high— 1160 ions were formed per cm. path by a neutral helium atom of 10^8 cms./sec. velocity ; an electron with this velocity producing no ionization whatever.

These results were verified and extended by Batho for Ne, A, Kr ions in the same gases at 10–20 KV. A high velocity neon atom had to make about thirty collisions

before it was ionized, while the ion required some five collisions before being neutralized. The numbers for argon were 60 and 5 respectively.

Secondary Emission.—Positive ions like electrons liberate secondary electrons when they impinge on a metal surface. The interaction with the surface in the former case is, however, more complex, since simple calculation shows that, assuming the process is the same, a hydrogen atom of 2·2 KV. would be equivalent to 11-volt electrons (the minimum for secondary emission) ; actually, 900-volt hydrogen ions are sufficient. In fact, Penning found that neon ions of 7-volt energy approaching a surface give secondary emission.

As with electrons, the factors influencing the emission are nearly the same. They are (1) nature of surface, (2) nature of impinging ion, (3) type of target.

For low voltage K^+, Jackson found first evidence of secondary emission from untreated Al, Ni, Mo at 100, 150, 300 volts respectively. Cs^+ was more effective and Na^+ and Rb^+ less effective than K^+.

Proper degassing raised the voltage required by 100 per cent. The emission increased linearly with the energy of the ion, and was greatest for Al, being 7 per cent. at 1000 volts uncontaminated (14 per cent. contaminated).

The secondary electron velocity was small, usually less than 1 volt; the number of reflected positives was also small, roughly some few per cent.

Extensive work on these lines by Oliphant, using He^+ on Mo, has verified these general observations. The ratio of secondary electrons to primary positives reached a value of unity for normal incidence with a cold target at 1000 volts, this ratio increasing with angle of incidence on the target. The velocity distribution curve of the secondary electrons obtained by the retarding field method showed that generally they had low velocities of 2 or 3 volts, but that some proportion existed with velocities as high as 20 volts. This proportion increased with outgassed targets.

The mechanism of emission for slow rays has been

explained in terms of the ionization potential V_i of the impinging ions, and the work function ϕ of the surface. Calculation shows that the field due to a positive ion at a distance of 10^{-7} cms. from the surface is of the order of 10^7 volts./cm., i.e. sufficient to extract electrons from the cold surface ; these then may neutralize the slow ion, giving a system with potential energy $V_i - \phi$, which must have a positive value in order that secondary emission may occur.

With higher velocity ions, the experiments of Baerwald with oxygen and hydrogen up to 20 KV. show that the maximum secondary electron velocity is about 20 volts, the bulk of the electrons having velocities of only a few volts, while the ratio of secondary electrons per primary positive was about 5. These results were verified in general by Schneider with protons of 23–46 KV. energy striking Al and Cu.

Absorption and Scattering.—The absorption of positive rays as with electrons takes place as the result of a gradual diminution of energy by large numbers of collisions with electrons. Where the positive ion has sufficient energy to bring it close to the nucleus, the result of the collision is to give a scattered distribution which obeys the Rutherford scattering law, as is the case with α particles. Gerthsen, using a Geiger counter sensitive to currents of 10^{-19}–10^{-21} amps., has verified this for 30 KV. protons passing through celluloid films up to 100 $\mu\mu$ thick.

Generally, with gases, small angle scattering occurs as found by Frische with low velocity K^+ in argon and by Thomson with protons of 5–25 KV. energy. The collisions of high voltage positive ions with gas molecules involve little change in direction or velocity at pressures of the order of 10^{-3} mm., i.e. in those cases where little if any ionization occurs. The work of Eckard with 30–51 KV. energy hydrogen rays shows that the velocity loss on passage through thin celluloid films (20–340 $\mu\mu$) varied proportionally with the film thickness. The loss in velocity was attributed to loss of charge, neutralization

and scattering, and appeared to be independent of the velocity of the rays. This is somewhat surprising, since the work of Baerwald with 19–46 KV. rays showed that, assuming the velocity loss was due to ionization, the number of ion-pairs produced per positive ion per cm. per mm. pressure in air, increased linearly with velocity from about 20–30, and the same sort of law would be expected to occur with thin solid films. Further, Eckard finds that the energy loss increased with increasing velocity of the particle, unlike the case of α particles where the ionization was a maximum towards the end of the range, i.e. for lower velocities. Gerthsen considers that this type of velocity loss must have a law for the range R given by $R = kv^x$, where x is < 2. In fact, the law $R = kv^{1.5}$ was found to express his results for the passage of protons through air and hydrogen. The interpretation of results for positive ion transmission through matter is somewhat difficult, owing to the complex changes such as transfer of charge and energy, etc., which the positive ion may undergo on collision. Thus, Gerthsen shows that He^+ is to a large extent transformed into He^{++} on passage through matter, when it has a velocity equivalent to about 100 KV.

Theoretically this figure can be verified, assuming a simple collision process to occur.

Nuclear Bombardment.—High-speed bombardment of atomic nuclei, using protons and molecular hydrogen rays, has given interesting clues as to their structure. All previous results in this direction had been obtained with α particles having energies of the order of five million electron volts. The substitution of a source of protons easily controlled both as regards speed (up to 2–3 million volts) and intensity, and free from objectionable γ-ray effects, has certainly been a big improvement, which is likely to lead to far-reaching results.

A further advantage of using protons is that on Gamow's theory of artificial disintegration, they have a greater probability of penetrating the nucleus than α particles of equal energy.

Cockcroft and Walton in their earliest experiments used a mixture of protons and hydrogen molecular rays accelerated through 300 KV. and bombarding targets of lead and beryllium (probability in the latter case was 6.2×10^{-3}). They obtained a non-homogeneous radiation, emitted at 280 KV., but its intensity was very weak, being only of the order of $\frac{1}{10000}$ of that produced by an equal electron source. Previous work by Barton, with electrons and protons of up to 25 KV. energy striking a copper target, had shown that no detectable X-radiation was produced by proton currents of 10^{-9} amps., whereas detectable X-radiation was produced by electron currents of 10^{-14} amps., the X-ray efficiency of electrons being some thousand times that of protons.

Extension of the work of Cockcroft and Walton to over 700 KV. with currents of 1 μA and upwards, imping-ing at 45° on a lithium target, gave α particles liberated from the lith-ium nuclei by the pro-ton bombardment.

FIG. 18.

These produced bright scintillations on a zinc sulphide screen, and had a range in air of 8·4 cms., which did not appreciably change with increased voltage. Their curve shows the number of disintegrations per minute per μA at various accelerating voltages and indicates one dis-integration per 10^9 protons at 250 KV.; this increases to 10 at 500 KV.

The kinetics of the disintegration process have under-gone some fundamental changes since the discovery of the neutron by Chadwick. The neutron is supposed to consist of a proton and electron tightly bound together

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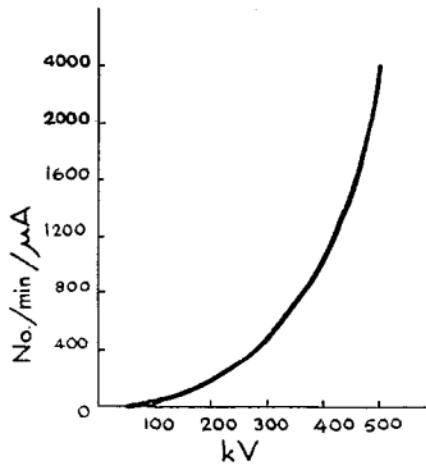
as a single unit, having a mass approximately equal to that of the proton, but with no net charge. Evidence of its presence was afforded by the radiation emitted by α-ray bombardment of boron, as it was equivalent to 10×10^6 electron volts, i.e. greater than any known γ-radiation. Further, the observations of Curie and Joliot that these radiations from Be and B could liberate protons from substances containing hydrogen, with a velocity of 3×10^9 cms./sec., necessitated a quantum of 50×10^6 volts if considered in the light of the Compton effect. This had to come from the interaction of the Be nucleus with an α particle of 5×10^6 volt energy. This was obviously a difficulty which was removed by assuming that the radiation consisted of neutrons. The liberated protons had a maximum range of over 40 cms. in air, with a maximum velocity of $3 \cdot 3 \times 10^9$ cms./sec., which is equivalent to an energy of $5 \cdot 7 \times 10^6$ volts. This is the energy with which neutrons are liberated from Be by α-ray bombardment, so that the reaction represented as follows consists in a transfer of energy from the neutron to the nucleus, which, for the case where hydrogen is present, gives the protons (recoil atoms) all velocities up to that of the incident neutrons :

$$\alpha \text{ particle} \mid \rightarrow \text{Neutron} \rightarrow \mid \rightarrow \text{Proton (recoil atoms)}$$
$$\text{(N)} \qquad\qquad \text{(P)}$$
$$\text{Be or B.} \qquad \text{Hydrogen.}$$
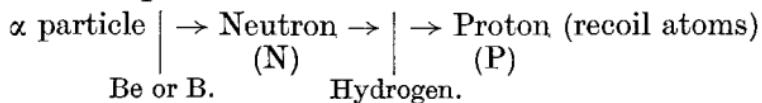
The α particle of course consists of $(2P + 2N)$.

The disintegration of aluminium results in capture of the α particle as follows :—

$$\alpha + (6\alpha, 1P, 2N) \rightarrow (7\alpha, 2N) + P$$
$$\text{Aluminium.} \qquad \text{Recoil} \qquad \text{High-speed}$$
$$\text{Silicon.} \qquad\qquad \text{proton.}$$
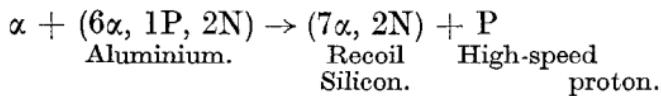
With boron, capture of the α particle takes place as follows :—

$$\alpha + (2\alpha, 1P, 2N) \rightarrow (3\alpha, 1P, 1N) + N$$
$$\text{Boron.} \qquad \text{Nitrogen recoil.}$$
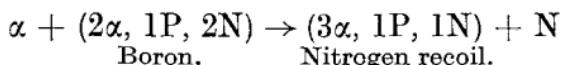
In Cockcroft and Walton's experiments,

$$(1\alpha, 1P, 2N) + P \rightarrow 2\alpha.$$
$$\text{Lithium.}$$
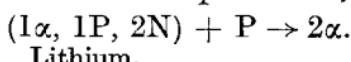
Calculation from mass defect in the disintegration process agrees with the observed range of the α particles. Extension to other elements has shown similar effects, the actual number of disintegrations obtained being in the following order : Li, B, F, C, Al, Ca, Co, Ni, Cu, Ag, Pb, V.

The most outstanding difficulty in connection with nuclear disintegrations appears to be the fact that such disintegrations were observed with elements of high atomic number, although, theoretically, this should not occur for these comparatively low energy particles.

An explanation might, however, be advanced on the lines of the resonance disintegration produced by α particles as put forward by Pose and Hafstad. They envisaged disintegration protons produced by such a process ; however, the matter is still unsettled. The experimental results on the nuclear disintegration of lithium obtained by Cockcroft and Walton were confirmed by Lawrence, Livingston and White and by Henderson, who worked with protons of over 10^6 volt energy. The latter finds that the number of disintegrations per proton, as well as the range, vary proportionally with the 3/2 power of the proton energy. His curve expressed in the form $N = 0 \cdot 0037 \, Ve^{-\frac{1600}{\sqrt{V}}}$ more or less agrees with the curves by the other authors when the presence of $H_2{}^+$ is taken into account.

In the case of the disintegration of Al by protons of $1 \cdot 2 \times 10^6$ volts Lawrence and Livingston got a radiation with a continuous distribution of range up to 8 cms. in air, the larger number of particles having the smaller ranges, and conclude that the proton disintegration energy varies approximately as the atomic number. This, however, was not found to be so by White and Lawrence, who got nearly the same yield of α particles from boron as from lithium above 500 KV.

Regarding bombardment by heavier particles $-H_2{}^+$ (deutons) the experiments of Lawrence and Livingston, with currents of 3×10^{-8} amps of $1 \cdot 3 \times 10^6$ v. deutons, have given extremely high neutron yields. Beryllium

liberated 5000 recoil protons per minute, which is equivalent to 10^7 neutrons per sec. The liberated protons have a range in air of 40 cms., and the reaction might possibly consist in the disintegration of the deuton itself, since the proton yield varied with the neutron yield.

The most recent work of Lauritsen and Crane with deuton currents of 10 μA. bombarding carbon at 900 KV., appears to show the presence of a penetrating γ-radiation with an absorption coefficient of 0·35 cm.$^{-1}$ and with very little neutron liberation—the reaction probably taking place as $C^{12} + H^2 \rightarrow C^{13} + H' + \gamma$. Another type of reaction which may occur in deuton bombardment is the liberation of α particles as shown by Oliphant, Kinsey and Rutherford. This has been verified by Lewis, Livingston and Lawrence, who utilized the deuton source obtained when $H^+H_2^+$ of 2×10^6 volt energy impinges on a target and breaks up, giving H^+(660 KV.) and H_2^+(1·33 $\times 10^6$ v.). They bombarded nitrogen with H_2^+ and got α particles liberated even at 600 KV., while at $1·33 \times 10^6$ volts, 100 α particles were liberated per 10^9 deutons—all apparently homogeneous and with a range of 6·8 cms. Similarly, Li and Be emitted α particles with ranges of 8·2 and 3·3 cms. respectively. Further work with C and $1·2 \times 10^6$ volt-deutons gave protons with a range of 18 cms. in air. The main point about deuton bombardment is the considerably larger number of disintegrations obtained as compared with protons.

Bombardment by still heavier particles He^+ at 10^6 volts, according to Crane, Lauritsen and Soltan, produces in the case of Be an intense source of neutrons. With the heavy mercury ion at $2·4 \times 10^6$ v. indications of the presence of an X-radiation was obtained by Coates, since the absorption in aluminium followed the exponential law. There was no continuous range in wave-length, as is the case when electrons are used, nor did the wave-length vary with the energy of the beam. The wave-length emitted appeared characteristic of the K series with light targets, while for heavy targets it was characteristic of the impinging mercury ion.

CHAPTER V

AIR AS A DIELECTRIC

Discharge in Air at Small and Large Spacings.—The changes in the electrical properties of air whereby it changes into a conducting condition are gradual, and depend on the voltage applied, distance, and shape of electrodes.

The curve showing the breakdown of air between parallel plates at atmospheric pressure consists of three distinct parts : (a) Ohm's law is here obeyed ; (b) constant current at increasing voltage, showing that the number of ions captured by the field must be equal to the number generated by the ion-producing processes ; (c) current increases rapidly with voltage. This is the stage defined by Townsend's "Ionization by Collision" hypothesis. New ions are here formed due to collisions of positive and negative ions with neutral molecules, thus increasing the available current carriers to a large extent.

FIG. 19.

The following are the types of discharge met with :—

(1) **Dark Discharge.**—Here the current, usually of the order of microamperes, increases slowly with voltage ;
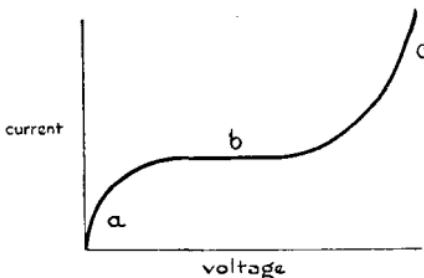
nothing is visible between the electrodes—the discharge is unstable, and is in its earliest stage.

(2) **Glow Discharge.**—Occurring at higher voltage than (1), and characterized by a bright glow extending throughout the column of gas, and enveloping the electrodes ; the current is of the order of milliamperes, but can reach tens of amperes in special cases.

(3) **Brush Discharge.**—A form of unstable glow, consisting of irregular streamers starting at some point and diverging outwards as a spray of blue or bluish-white light. It is possible to get electrical rectification by the brush discharge, owing to the unequal mobilities of positive and negative (newly born) ions in the air surrounding the electrode.

(4) **Spark and Arc Discharge**—The air has become an excellent conductor, and its current-carrying capacity is limited only by the external circuit. The characteristic of the latter type is the fall in voltage across the electrodes with increasing current, i.e. the characteristic has a negative slope.

FIG. 20.

When the distance between two spherical electrodes (of 1 in. diameter, say) is varied, the initial discharge consists of a glow round the electrodes, the voltage required to produce this glow increasing with the spacing according to SOD.

Up to the point O the sparkover voltage for the system is practically the same as the glow voltage, but above O higher voltages are required for sparkover. The spacing SX corresponding to the point O is known as the critical distance for this particular arrangement, and in this case is approximately three diameters.

Goodlet, Edwards and Perry investigated such curves for sphere to plate gaps at distances up to over 10 ft. Their results, while confirming the above, show that both
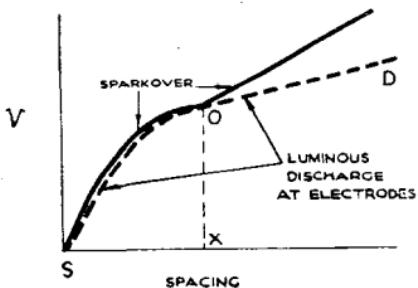
SX and the glow voltage increase with the electrode dimensions. At very large spacings the sparkover curve tends to coincide with that for the point plane gap, as is to be expected.

Corona.—Up to a spacing SX, sparkover takes place simultaneously with the luminosity which first appears at the electrodes ; above this critical spacing, a distinct pale violet glow covers the electrodes, accompanied by a rather characteristic hissing noise. This is the corona point, and indicates the existence of an unstable form of discharge in the air, which is partially broken up into ozone and oxides of nitrogen in the immediate vicinity of the electrodes. Sufficient increase of voltage at this stage again results in sparkover. Corona and consequent sparkover are only possible in non-uniform fields, i.e. for those with a varying gradient. With corona on two parallel wires in air, the negative wire seems studded at regular intervals with reddish beads, the intervals between the beads showing oxidation, while the positive wire is covered with a light blue glow. The formation of the beads on the negative wire appears to depend on the nature of its surface. Polished wires always give the beads, while corroded and enamelled ones do not. The presence of drops of water or oil on the surface, because of their high dielectric constant, cause a lowering of the corona starting voltage, as also does enamelling of the wire. The presence of additional ions from X-ray and ultra-violet sources in the immediate vicinity of the electrodes has no direct influence on the corona starting voltage, the "natural" ions already present being sufficient. Humidity of itself has no effect except in so far as it lowers the air density, and if so, must be allowed for, as shown later. Peek found no special effects due to frequency up to 20,000 cycles, but at very high frequencies the starting voltage for corona was somewhat lowered.

With **parallel wires** in air the gradient g_w at the surface required for corona formation appears to be independent of the spacing S, where this is large compared with the wire radius r cms.

Peek gives $g_w = 30\left(1 + \dfrac{0\cdot301}{\sqrt{r}}\right)$ KV./cm. maximum.

The gradient g_w can also be defined in terms of the voltage V between the wires and their dimensions as

$$g_w = \frac{V}{r \log_e \dfrac{S}{r}}.$$

Thus, as r decreases, g_w increases, and may reach a value of several hundred KV./cm. for very thin wires before corona can form on them. With two brass rods 1 in. diameter, spaced 2 ft. apart, corona will first appear when $g_w = 30\left(1 + \dfrac{0\cdot301}{\sqrt{1\cdot27}}\right)$ KV./cm. = 38 KV./cm.

The gradient is greatest at the wire surface, and falls off as the distance from the surface increases. Peek has shown that the gradient at a distance $0\cdot301\sqrt{r}$ from the wire surface is always constant at 30 KV./cm. for all radii. The ionic processes which culminate in corona or partial breakdown of the air, hence must take place within this distance. It thus appears that in order to obtain corona, initial gradients in excess of 30 KV./cm. at the wire surface are necessary. This value defines the " electric strength " of the air.

A very common electrode system met with in practice is the **coaxial cylinder** arrangement. With a thin wire radius r as the inner cylinder Peek gives the corona gradient

$$g_w = 31\left(1 + \frac{0\cdot308}{\sqrt{r}}\right) \text{ KV./cm. max.}$$

when $r = 0\cdot01$ cm. ; $g_w = 125$ KV./cm. max.

The gradient appears to depend only on the radius of the inner cylinder, and to be independent of that of the outer cylinder.

Booth investigated the field distribution for the balanced field of this system by inserting a small insulated spherical probe into the field, and taking potential

measurements with delicate electrostatic voltmeters of small capacity.

His curves (Fig. 21) for a 20 B and S wire in a $3\frac{1}{2}$ cm. radius cylinder show—

(1) within the first $\frac{1}{2}$ cm. from the wire, and whether positive or negative, there is a steep fall of potential by over half the total value;

(2) the potential fall soon after becomes nearly constant to within a small distance from the mouth of the cylinder—the electric force within this region thus vanishes;

(3) there is an abrupt potential fall over a small distance near the mouth of the cylinder.

The forms of curve for the corona glow, whether well developed or barely perceptible, remain the same. Such curves, if taken all the way up to sparkover and at various pressures, should be of value in helping to elucidate some aspects of sparkover in non-uniform fields.

FIG. 21.

It was pointed out in connection with the use of the sphere gap as a measuring instrument that, for reliable results, the separation of the spheres should not be greater than their radius. The reason for this is that when the spacing is a multiple of the radius (> 3), the corona which then forms leads to inaccurate results. For corona to form on **spheres** Peek has shown that the necessary gradient at the surface is given by

$$g_s = 27 \cdot 2\left(1 + \frac{0 \cdot 54}{\sqrt{r}}\right) \text{ KV./cm. max.}$$

A curve plotted out for values of g_s and r shows that when r is about 5 cms. and above, g_s becomes sensibly constant
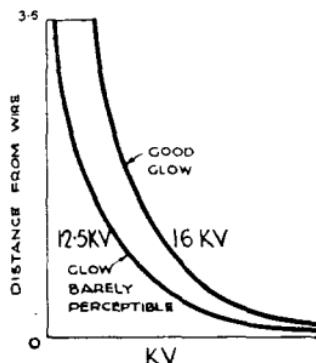
at 30 KV./cm., the "electric strength" of the air; thus approaching more and more to the ideal of the uniform field—that between parallel plates.

Peek's curve between g_s and spacing for any particular radius of sphere shows that below a spacing of $4r$ no corona forms, and the first evidence of discharge is sparkover.

Above this spacing corona precedes sparkover, and the voltage required for sparkover exceeds that for corona, and rises more and more rapidly as the spacing increases.

The curve shows how very steeply the gradient increases at spacings below about $0.54\sqrt{r}$. Peek has shown further that at a distance of $0.27\sqrt{r}$ cm. from the sphere surface, the gradient for breakdown is nearly constant, irrespective of the spacing between the spheres, a condition somewhat analogous to that previously discussed in the case of parallel wires.

Fig. 22.

The rectifying action due to corona has been known for some time. The only drawback to utilizing the effect in a practical way is that the net amount of charge is too small. It has been found that for the case of a **point and plane** more current flows in the circuit when the point is positive than when it is negative.

With blunt **point electrodes**, Zeleny found that the discharge occurred at a lower voltage with the point positive than when it was negative; with sharp points, on the contrary, he found the reverse to be the case.

Effect of Pressure on Corona.—From the general discharge theorem laid down by Townsend, that the potential at which a discharge starts is a function of the
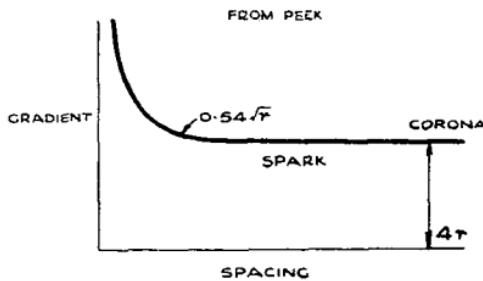
density of the gas, and the linear dimensions of the electrode system, it can be inferred that the corona gradient must likewise be some function of these quantities—in fact, it can be shown that the corona gradient is directly proportional to the density of the gas, other things remaining the same. Peek shows that in the case of a wire and concentric cylinder, the gradient at the wire $= 31p\left(1 + \dfrac{0 \cdot 308}{\sqrt{pr}}\right)$ KV./cm. max., where $p =$ pressure of gas (air) ; $r =$ radius of wire. This equation has been found to hold down to pressures of a few cms. of Hg.

For spheres, $g_s = 27 \cdot 2p\left(1 + \dfrac{0 \cdot 54}{\sqrt{pr}}\right)$ KV./cm. max., and for parallel wires, $g_w = 30p\left(1 + \dfrac{0 \cdot 301}{\sqrt{pr}}\right)$ KV./cm. max. In the latter case a higher voltage is required to produce negative corona than that for positive corona for all pressures down to 1 mm. Hg ; below this pressure the reverse is the case.

The effects of temperature (t) must be taken into account by the corresponding change in density which it produces, the density (d) being given by $\dfrac{3 \cdot 92p}{273 + t}$; hence, in each of the above formulæ for the gradient, it will be necessary to substitute this factor for the pressure p, whenever both pressure and temperature have to be taken into account. When the pressure falls below about 1 mm. Hg, the above laws no longer hold. The molecular mean free paths now become comparable with the dimensions of the apparatus, and other factors hitherto neglected or considered unimportant at the higher pressures must be further considered. Meservey has investigated such effects for air from pressures of 1 mm. Hg and lower in the case of the concentric cylinder arrangement.

He finds that for any particular pressure, corona forms at a lower voltage with the inner cylinder negative than when positive, and, further, that there seems to be some

particular pressure, different for each type, at which the corona voltage is a minimum.

At still lower pressures negative corona as such no longer appears, although positive corona can still be detected. This soon gives way to a type of vacuum discharge when the voltage is sufficiently increased.

Current in Corona Discharge.—In designing high voltage apparatus, the electrodes and spacings must be so dimensioned that gradients above the critical corona gradient are not exceeded (except for some very special and unique cases), otherwise there will be a loss of power and efficiency due to the corona currents which flow through the intervening air. These currents can be quite appreciable—certainly tens of milli-amperes per metre length, at several hundred KV. with a correspondingly heavy power loss. In laboratory work the wire and concentric cylinder arrangement constitutes a useful source of leakage current whose limits can be

CONCENTRIC CYLINDERS

Outer diam 12 7″ } Length 70″
Inner (wire) 1 mm

Corona observed at approx 30kV
A.C Sparkover 107 kV

Corona current (mA)

kV across condenser
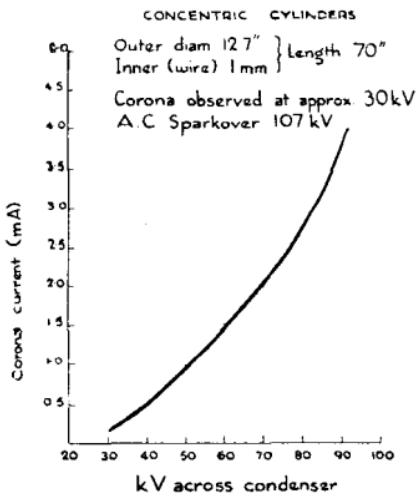
FIG. 23.

easily controlled by altering the diameter of the wire. The curve shown by the author was taken for such a system on D.C.; the calculated corona voltage agreeing with the visual observed voltage (in the dark).

The corona current i in such a system is given by

$$i = kV(V - V_c),$$

where V = applied voltage,
   V_c = voltage at which corona appears,
   k = a constant depending on the radius R of the
      external cylinder and approximately $\propto \dfrac{1}{R^3}$.

The power loss in this case is given by

$$iV = kV^2(V - V_c).$$

Townsend gives i, the current per unit length for positive corona, $= \dfrac{V(V - V_c) \cdot 2k_1}{R^2 \log \dfrac{R}{r}}$, where $k_1 =$ mobility of positive ion.

This formula, when applied to the experimental case cited above, gave values of current of the right order of magnitude.

Peek has investigated at great length the variation of power loss with voltage on parallel transmission lines and has experimentally verified the quadratic form of the loss curve at the higher voltages.

Sparkover.—Sparkover, or complete temporary breakdown of the air between the electrodes, will occur when the gradient is sufficiently increased to cause local breakdown. This soon spreads throughout the whole of the inter-electrode space and gives the required number of ions to carry the current—which can be tens of amperes. Simultaneously with this sudden increase in current, there is a corresponding fall in voltage across the electrodes to a very low value, the slope of the characteristic now being negative. The processes which lead up to a spark in air had for a long time seemed obscured owing to the experimental difficulties involved. The fact that the spark lag, i.e. the time it takes for spark conditions to " build up," was of the order of 10^{-8} secs. led to the application of the high-speed cathode ray oscillograph by Rogowski for recording the potential variations that occur across a gap.

In addition to this, the detailed examination of the Kerr cell by Beams, and the experiments carried out with its aid by Lawrence and Dunnington, have helped considerably in unfolding the nature of an air spark. The Kerr cell consists of two copper plates immersed in carbon bisulphide. When a potential difference is applied to the plates the carbon bisulphide acquires the property of becoming doubly refracting, i.e. the

light it passes is polarized : this property disappears as
soon as the voltage across the plates is removed.

The cell is placed between crossed Nicol prisms, hence
the combination will pass light only if voltage is impressed
across the cell.   This " shutter " will thus be open for the
period for which the voltage lasts across the cell.

In Lawrence and Dunnington's arrangement the cell
is open during the initial stages, during which the voltage
is rising across the gap.   As soon as the gap sparks over,
the light from the gap is passed by the cell for such a time
as the voltage wave takes to collapse, i.e. is determined
by the length of wire from gap to cell divided by the
velocity of light.   By altering the length of wiring to
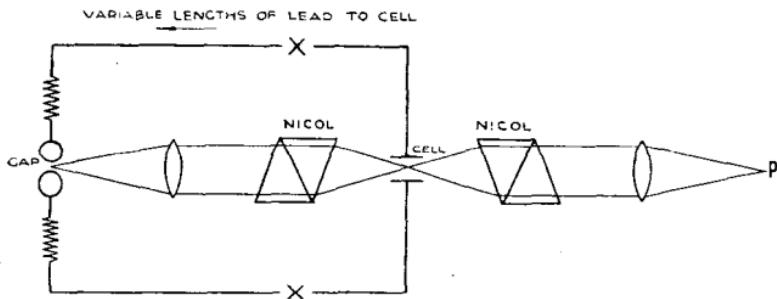
FIG. 24.

the cell, the time for which the cell is open can be auto-
matically altered up to 50×10^{-8} secs. (Fig. 24).

In its very early stages the spectrum of the discharge
consists of air lines with no metallic lines whatsoever.
As the discharge develops, the lines of the metal of the
gap begin to appear, but are broadened due to the Stark
effect.   Calculations from the observed broadening in-
dicated inter-ionic fields of average value of 10^6 volts/cm.
at this stage.   The average velocity of migration of the
metallic ions during the first $27(10^{-8})$ secs. was found
to be $2 \cdot 5 \times 10^5$ cms./sec.   The discharge, as revealed
by the photographs, takes the form of a thin streamer,
narrow at the anode and gradually broadening to about
four times the anode area of order (10^{-4}) cms.^{2}, on reaching

the cathode, the current density being of the order 10^6 amps./cm.² (Fig. 25).

Further inferences showed that about one-third of the molecules in the discharge path had been ionized. Such intense ionization was accounted for on Saha's thermal ionization theory, a temperature in the region of 10,000° K. being necessary for a satisfactory explanation.

The nature of the electrode surface in sparkover tests is rather important. Large surface discontinuities, producing local discharges, give potentials of too low a value ; the same effect has been recorded by Peek for surfaces contaminated by oil, moisture or dirt. The extensive tests carried out by the E.R.A. on spheres of brass, phosphor bronze and mild steel showed that polishing with " metal polish " on cotton wool and finishing with chamois leather gave consistent results. Microscopic examination of the surface revealed scratches,
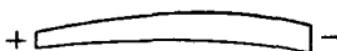
FIG. 25.

which probably helped to keep the sparkover voltage regular and are thus desirable. Further polishing with a rotating buff gave even more consistent results. With high frequency, the surfaces must be well polished for accurate work ; local irregularities on the surface giving reduced sparkover voltage, due to brush discharge.

The work of Whitehead and Castellain has shown that for 20 mm. spheres, humidity (75 per cent. in clean air) causes a slight decrease in sparkover voltage. On the other hand, in the case of the needle gap, the reverse holds true—a definite increase in sparkover voltage occurs with increase in humidity.

Paschen's Law.—In the case of uniform fields in air and other gases, Paschen's Law can be briefly stated as follows : the sparking potential is proportional to the product of spark length (l) and gas pressure (p), i.e. proportional to the mass of gas or number of molecules

between the electrodes. This has been experimentally confirmed for values of p (mm.) $\times l$ (cms.) up to 20,000 in air, i.e. for sparking distances of about 30 cms. at S.T.P. When this product falls below about 1, the law no longer holds, the slope of the curve now being in the opposite direction. Thus, for any fixed spark length there is a critical pressure for which the sparking potential is a minimum (Fig. 26).

With spherical electrodes in air at short spacings, Hayashi found the sparking potential to increase linearly with pressure up to about 10 atmospheres. Above this the curve slowly flattens out. He also found that for short spark lengths ($\frac{1}{2}$-$1\frac{1}{2}$ mm.) at 10 atmospheres and above, the sparking potential is not proportional to the spark length for any particular pressure.

FIG. 26.

Peek, working with short needle points in air (up to $\frac{1}{3}$-in.) finds the sparking voltage approximately proportional to pressure up to 14 atmospheres. Above this, there is a decided fall in voltage, and little further rise takes place up to 100 atmospheres.

Sparking : Electrode Systems.—With **point and plane** results are somewhat erratic, because sparkover voltage depends on " sharpness " of the point. The sparkover is usually preceded by the dark discharge and corona. With care a linear calibration more reliable at the larger spacings and having a slope of about 5 KV. max./cm. is obtained : this figure is helpful in estimating sparking distances in H.T. circuits. It is interesting to note that at ordinary pressures in air the sparkover voltage with
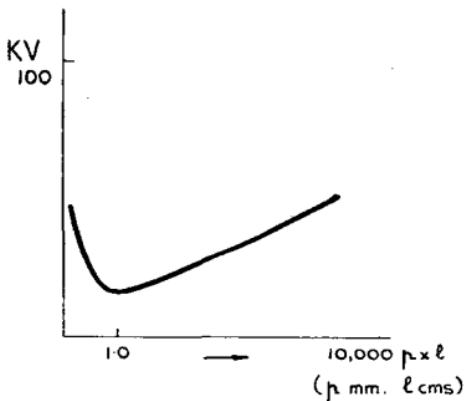
the point positive can be less than half that when the point is negative : this effect tends to reverse with decreased pressure.

Reliability with the **needle gap** (No. 00 sewing needles) is limited to the region 10–30 KV. Below or above these respective values humidity effects, incipient brushing, etc., tend to put the calibration out. Above 30 KV. the slope is about 4·2 KV. max./cm.

When used on continuous high frequency, the needles as well as the air gap become quite hot, and the spark-over voltage readings are too low. On the other hand, with impulses, the reverse is true, the gap readings indicating too high a voltage.

For measuring high-frequency voltages, as well as steep wave-front impulses, the **sphere gap** is very re-liable. Within the spacing $0·54\sqrt{r}$ to $2r$, the gradient is practically constant, and the ideal uniform field is approached ; the sparkover voltage is then a linear function of the spacing and the system is calibrated for this region.

Above spacings of $2r$ the gradient increases, and at spacings of $4r$ and upwards corona appears, the spark-over voltage now increasing more rapidly than the corona voltage.

The ratio of outer and inner cylinders in the **concentric cylinder** arrangement determines whether or not the first sign of discharge is a spark. If this ratio is $> 2·78$, corona will first form and the sparking voltage will be much greater than the corona voltage. If the ratio is $< 2·78$, no corona will form on the inner cylinder, and the breakdown voltage is the sparkover voltage.

Peek explains the sparkover by assuming a partial breakdown which starts as a corona at the inner surface, and extends to a distance $0·3 \sqrt{r}$ from that surface, to where the gradient falls below g_0(30 KV./cm. in air). When this critical distance is comparable with the distance between the cylinders, complete sparkover will take place.

5

The partial breakdown of the air in the case of **parallel wires** extends to a distance from the wire surface to where the gradient falls below 30 KV./cm., as above. If the ratio of spacing to radius is < 30 sparkover is the first evidence of discharge ; if > 30, corona appears first, the corona gradient being independent of spacing. This is followed by sparkover, usually at a higher voltage, which varies linearly with spacing.   As the radius of the wire decreases, the gradient as well as the sparkover voltage increase.

Spark Lag.—The " spark lag " can be defined as the time taken by the various ionizing processes and agencies to build up such a condition in a gap, that sparkover or temporary breakdown of the insulating properties of the air occurs.   Pedersen, Rogowski, Torok and Beams, by applying overvoltages of 50 per cent. and above to two parallel plane electrodes, got the spark lag to be of the order of 10^{-8} secs.

FROM PEEK

FIG. 27.

The experiments of Lawrence and Dunnington have verified this.   Loeb, working on the hypothesis of abnormal gradients in the gap has also conveniently explained this short time-lag.

With the needle gap, the time-lag may be quite large, because of the large mass of air to be broken down.

With a gap the impulse ratio, i.e. the ratio for breakdown with rapidly applied voltage to that with D.C. or 60 cycle voltage, defines its " time lag " for any particular voltage wave.   Thus V_{t_1} is the D.C. breakdown voltage of the gap in time t_1 ; V_{t_2} is the steep wave voltage causing breakdown in a time t_2 shorter than t_1. With steeper impulses larger overvoltages can be applied before breakdown, the time for which the impulse lasts becoming shorter and shorter the steeper the impulse.
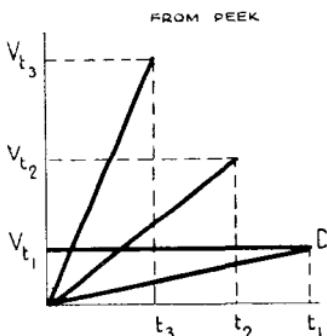
With the sphere gap the impulse ratio is practically unity (as it is with all uniform fields), even with steep waves which reach their crest values in 1/10 microsecond.

With the needle gap impulse ratios as high as 3·5 have been recorded. In this connection it is interesting to mention that Peek used in his experiments a 5 million volt generator capable of giving waves of from a few microseconds to over 1000 microseconds in duration, the sparkover distance with the latter being 28 feet.

Investigation of factors which influence the " time-lag " has revealed the importance and effects on the gap of external ionizing radiations. It has been known for a long time that these help to give consistent results with a sphere gap.

Whitehead and Castellain found a small tendency to lower sparking voltages with their 62·5 mm. spheres when irradiated with ultra-violet light. This has been verified with the three-point gap, a device in which the main gap between two points is influenced by an auxiliary discharge to the third point. With this arrangement, the " time-lag " of the main gap is more or less eliminated by the radiations of wave-length 13–1000 Å., which proceed from this auxiliary gap ; this is the only factor which is necessary to give the desired effect ; subsidiary effects due to the auxiliary gap, though helpful, are not essential.

SOLIDS AND LIQUIDS AS DIELECTRICS

On the classical electro-magnetic theory propounded by Maxwell, all dielectric behaviour could be explained in terms of the two characteristic properties of a dielectric—its specific inductive capacity K and its electrical conductivity ρ, the total displacement in a dielectric under electrical stress being $P = \dfrac{K}{4\pi} \cdot \dfrac{F}{v^2}$ e.m.u.,

where   F = field,
        v = velocity of light,
        P = polarization or dielectric strain.

The larger K, the greater the electric displacement, the latter being directly proportional to, and in the direction of the field. This displacement is only momentary and when the field is removed, the displaced electrons can return to their original position, giving a displacement now in the reverse direction. These are the familiar charge and discharge currents of a condenser.

Superposed on this displacement current is the normal conduction current through the dielectric, obeying Ohm's Law, and depending on the insulation resistance. This leakage current starts at a comparatively large value and decreases with time to a fairly constant value, owing to the building up within the dielectric of space charges, which sometimes alter the field quite considerably.

Abnormal Properties of Dielectrics.—The dielectric phenomena of absorption of charge and power loss in

alternating fields are known as anomalous properties, since these should be non-existent for perfect dielectrics.

The absorption current which is superposed on the normal displacement and conduction currents is at first large and then decreases over a period of several hours, to zero, the total current being then the conduction current. This absorption of charge is completely reversible only in the case of solids ; the resulting quantity of electricity, in abnormal discharge, is, according to the Hopkinson Superposition Principle, equal to that for abnormal charge. The detailed work of Wagner showed that the abnormal charging current varied during short time intervals according to the law $I_a = Bt^{-m}$, where m is a constant < 1. In the case of an ideal dielectric, the current leads the voltage by 90°, but in practice this angle is diminished by a small angle α, which varies from dielectric to dielectric, and even with the same dielectric may vary with its past history. The power factor of the dielectric is given by $\sin \alpha$, and the total power loss is expressed as $IV \sin \alpha$, where I and V are R.M.S. values. It is clear that a dielectric with a high power factor will dissipate appreciable amounts of energy which will impair its electrical qualities.

Conduction in Solid Dielectrics.—The experiments of Warburg on the conductivity of glass, showed that the sodium ion carried the current from the positive electrode through the glass to the negative electrode. After some time, a negative space charge built up in a small and not clearly defined region round the positive electrode. As no more sodium ions were available the conductivity decreased, its rate of decrease depending on the time rate of formation of space charge. To get an accurate value for the conductivity, it is necessary to find its value before space charge builds up, or, to prevent electrode polarization, either by supplying the deficiency of the positive ion by external means, or by working with A.C.

Robinson has given some interesting curves for the

variation of true resistivity with temperature for soda lime glass up to 500° C.

He finds the law $\rho = \rho_0 e^{\beta/T}$ to hold, where ρ = resistivity and T = temperature, so that a straight line is obtained on plotting $\log \rho$ and $\frac{1}{T}$ (Fig. 28).

In addition, he has investigated the effect of frequency. It is seen from his curve that there is an additional loss due to frequency. This increases with the frequency at the lower temperatures, but disappears at the higher temperatures.
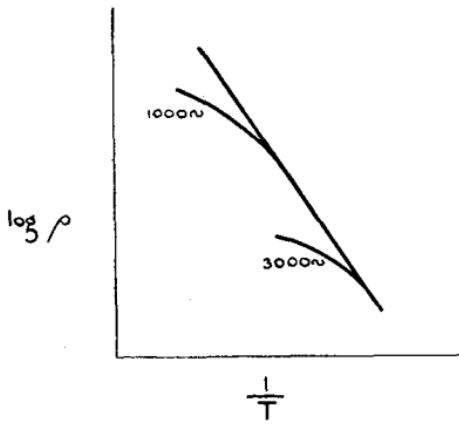
FIG. 28.

Poole has investigated how the electrical conductivity of thin sheets of mica and glass ($\frac{1}{100}$ and $\frac{1}{10}$ mm. respectively) varies with the field, and has found that log conductivity increases linearly with the field, the relation between them being given by $\log K' = A + BF$,

where   K′ = conductivity,
             F = field of order 10^6 v/cm.,
             A and B are constants.

Further investigations on these lines with extremely high fields might elucidate the mechanism of space charge formation during the various stages of build-up.

Care, of course, will have to be taken that the fields employed are not sufficient to cause partial or complete breakdown of the dielectric.

Breakdown.—The slope of the current-voltage relation for any dielectric is positive till a point is reached

on the characteristic at which the slope becomes negative and the current becomes unstable. This point determines the dielectric strength (voltage) of the insulation. This voltage is not constant even for the same batch of insulation, but depends on its past history. Also it is lower, the larger the electrode area, owing to the greater chance of weak spots. The breakdown usually takes the form of a puncture accompanied by charring, splintering or volatilization depending on the power short circuited. There is little doubt that thermal effects in the dielectric tend to precipitate breakdown conditions, since the conductivity rises steeply with temperature. The relation between breakdown voltage (B.D.V.) and thickness t of insulation is generally of the form B.D.V. $= kt + p$, where k and p are constants. For thin sheets of material B.D.V. $\propto \sqrt{t}$ which holds up to $\frac{1}{2}$ mm. for glass and up to 5 mm. for porcelain. For thicker sheets the curve flattens out, hence maximum strength is obtained with thin sheets. The very recent work of Jost indicates that for thin tantalum oxide films the dielectric strength varies directly with the thickness for films from 24–250 mμ, the breakdown strength being in the neighbourhood of 2×10^6 volts/cm., a gradient sufficient for liberating " field currents."

Some recent experiments of Terada, Hirato and Yamamoto are interesting in connection with surface breakdown. These authors examined the tracks produced by condenser discharge sparks along window glass. They obtained fine hair cracks about 3–5 μ deep, extending along the whole spark track and transverse to the direction of the spark. The breadth of the crack zone was proportional to the quantity of charge available, so that local surface heating effects increase the already existing strain in the surface layer.

Breakdown : Effect of Temperature.—Generally, increase of temperature decreases B.D.V. of all solids. A porcelain insulator, good for 70 KV. at 30° C., will breakdown at 20 KV. at 180° C. In this connection, four factors have to be considered : (1) structure of the material,

(2) temperature gradient in and out of the insulation, (3) superimposed heating effects of the conduction current, (4) heating effects are cumulative.

The theory of thermal instability based on (4) was first put forward by Walker and expanded by Wagner, who assumed a heterogeneous dielectric. Dreyfus, on the other hand, assumed a homogeneous dielectric which was electrically stable if its internal temperature did not exceed some particular value. Further deduction showed that B.D.V. $\propto \sqrt{\dfrac{\text{thickness}}{f(\text{mean temperature})}}$, provided there was no temperature gradient through the dielectric: if the latter did not hold, then B.D.V. varied inversely as

$$\sqrt{f(\text{mean temperature})}.$$

For some materials, e.g. glass, there appears to be a definite low range of temperature which has no influence on the B.D.V., which is then defined by the peak voltage: where heating effects occur, the R.M.S. value defines the B.D.V. Exceptions to the general rule, however, occur, as with wet or dry pressboard, where B.D.V. increases with temperature due to complex structural modifications not yet understood.

Breakdown : Power Loss and Frequency.—The power loss in any dielectric, given by $I_0 V_0 \sin \alpha$, can be looked upon as being dissipated in a resistance either in parallel (r_p) or in series (r_s) with the ideal loss-free dielectric. If I_0 and V_0 are the R.M.S. current and voltage, the equivalent parallel capacity is $C_p = \dfrac{I_0}{V_0 w} \cdot \cos \alpha$, while the equivalent series capacity is $C_s = \dfrac{I_0}{V_0 w} \cdot \dfrac{1}{\cos \alpha}$, where $w = 2\pi f$. The power factor $\sin \alpha \fallingdotseq \tan \alpha = \dfrac{1}{r_p C_p w} = r_s C_s w$, hence the power loss $= V_0^2 w k C_0 \tan \alpha$, where $k =$ dielectric constant and $C_0 =$ equivalent capacity for an air condenser. The power loss thus (1) $\propto V^2$ and (2) $\propto f$. Peek's experiments on varnished cloth verified (1) for

gradients of 12 KV./mm., while Fleming and Dyke and Addenbrooke verified (2) at moderate frequencies.

At very high frequencies an additional factor $\propto f^2$ enters, the power loss is $\propto f$ up to 500 k.c. and then falls (for crown glass), the maximum power factor not occurring at the same time as maximum power loss. Accurate knowledge of power factor indicates the quality and behaviour before and during life, and also the safe high voltage limit of the dielectric. Its low range of values (0·001–0·2) necessitates an accuracy of 1 in 10,000 in its measurement. This has been achieved by careful measurement, using delicate wattmeters ; the high

Crown Glass (Bairsto P.R.S. 96, 363. 1925
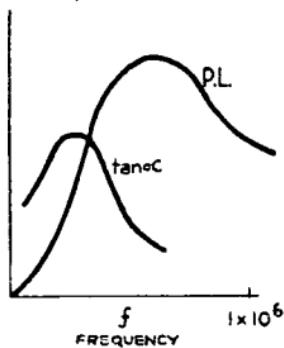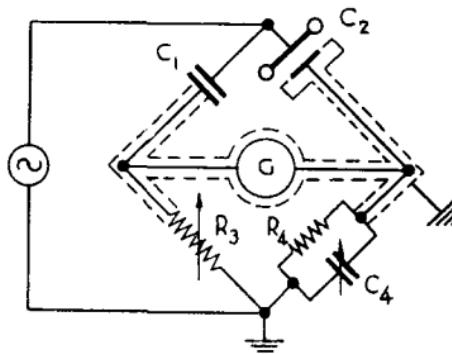
FIG. 29.   FIG. 30.

voltage (up to 20 KV.), electrostatic type has been described by Rayner, Standring, Davis and Bowdler. The use of the oscillograph, giving the wave-form of current and voltage as well as their phase displacement, is another ready method for obtaining power loss and power factor. The Schering bridge shown gives good results, and is a null method. C_1 is a standard condenser of known power factor, and the bridge is balanced by varying R_3 and C_4. Earth shields eliminate stray capacity effects. The power factor and power loss is then determined in terms of C_4 and R_3.

By finding when the power factor no longer changes with time at every impressed voltage, the maximum

voltage limit for any sample can be obtained without requiring a large batch.

Generally, the B.D.V. of a dielectric decreases with increasing frequency, due presumably to the greater power loss. Many exceptions are, however, known; thus for mica the (D.C.) B.D.V. was three times the 50-cycle value while there was little change between 50 and 50,000 cycles/sec. With high-frequency voltages, on the other hand, the decrease in electric strength is definite, the B.D.V. of mica at 200 k.c. being only 40 per cent. of that for D.C. Further confirmation of this has been obtained with glass, resin and porcelain.

Breakdown : Duration of Stress.—Generally, it is to be expected that the shorter the time of application of the voltage, the higher the voltage which can be applied before breakdown occurs. Results for impulse breakdown lasting from microseconds up to some thousandths of seconds are somewhat contradictory. Thus, Inge and Walther, working with glass and rock-salt, found no variation in B.D.V. with time of application of stress (up to 10^{-3} secs.), while Jost, on the other hand, showed quite definitely that such a variation existed. This is seen from his table.

Presspahn in Air (1 mm. thick).					
Time .	10^{-8}	10^{-4}	1·0	10^4	seconds
KV./cm. .	400	360	210	115	

The former authors maintain that partial breakdown occurs at some particular stress independent of time of application, and is completed in some time depending on the voltage available.

The work of the A.E.G., with impulses lasting up to tens of microseconds applied to discs of mica, micanite and porcelain, showed that the B.D.V. was considerably less than with continuous voltage. This is a most

unexpected result, as, by analogy with air, an impulse ratio of some sort is expected.

For longer time intervals (minutes), Peek shows that B.D.V. $= \underset{T=\infty}{\text{B.D.V.}} + \dfrac{k}{\sqrt[4]{T}}$, where $T =$ time, $k =$ a constant. By plotting B.D.V. against $\dfrac{1}{\sqrt[4]{T}}$, the B.D.V. at infinite time (T_∞) is obtained. This gives a measure of the insulating strength of the material. In the case of fibrous insulations, the application of an empirical law $nT = $ a constant, gives an indication of the life of the insulation under some particular conditions, and has been found very useful. Here, $n =$ number of applications of breakdown voltage, $T =$ time of each application as a percentage of total time for continuous breakdown, and must be at least 40 per cent. of that time.

In practice, for testing quality, the insulation is placed between 10 cm. diameter discs and voltage rapidly applied till breakdown occurs. The " minute " test is made by immediately placing 40 per cent. of this voltage on the specimen, and increasing the voltage by 10 per cent. of the rapidly applied B.D.V. per minute till breakdown occurs. The " endurance " or long-time test is carried out by placing 40 per cent. of the minute test voltage on the specimen, and raising the voltage in steps of 10 per cent. of the rapidly applied B.D.V. at intervals of one hour or so, till breakdown occurs. Discrepancies in B.D.V. values, even with the same material, can usually be traced to some differences in treatment during or after the manufacturing process.

Liquid Dielectrics : Conduction.—The process of conduction here is much the same as with solids—the initial large conduction current decreases with time, owing to the formation of space charges, and also to the removal of highly conducting impurities by the field. For an oil film, Black and Nisbet find $R = R_0 + bI$, where $R_0 =$ true resistance of film in absence of space charge, $b =$ a constant, $I =$ final steady current for gradients of (12 volts/cm. — 600 volts/cm.).

As with solids, an absorption effect occurs in addition which depends on the purity of the liquid, its temperature and the voltage gradient. This disappears when the voltage is removed, probably due to rapid neutralization of space charge, so that no discharge current is obtained, unlike the case with solids.

The conductivity falls with time of application of voltage, five or six hours sometimes elapsing before conditions are steady. Welo's curves show a small but distinct effect due to voltage gradient. By careful removal of all impurities normally present in hydrocarbons and transformer oil, he has shown how the conductivity falls with increase in purity of the oil for all gradients up to 8000 v./cm.

FIG. 31.

Finally, the work of Nikuradse and Russichurli with mineral oil has shown that the current-voltage characteristic is of the same form as with air —above a certain voltage, the current rises abruptly for very small increase in voltage. In the saturation current region, the current rises very rapidly with temperature, according to the law $I_t = I_0 e^{\alpha t}$,

where I_t = saturation current at temp. t,
         I_0 = saturation current at temp. o,
         α = temperature coefficient,

so that the log I, t curve is a straight line for any particular voltage up to their limit of 20 KV. between the electrodes.

Liquid Dielectrics : Breakdown.—The methods employed in studying breakdown of gases have also been applied with success in the case of liquid dielectrics. Rogowski, using the cathode ray oscillograph, showed the time of breakdown to be of the order of 10^{-9} secs.
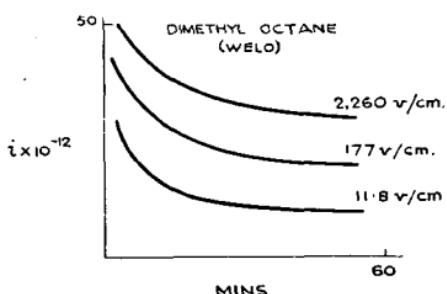
(cf. breakdown of air).   Photographic following through of the breakdown, using a modified Kerr cell arrangement, has also been used with success by Washburn. The breakdown is slower than for air, as the impulse ratio with oil is higher than with air, making this method very convenient. He was thus able to obtain photographs of both static and impulse breakdown in commercially pure paraffin oil and xylol, in time intervals as short as 0.06×10^{-8} secs. The photographs are markedly different from those for air, where there was ionization at both electrodes.   Here, however, the ionization appears to be mostly confined to the anode region, and for longer times (0.8×10^{-8} secs.); there were also cases where the ionization throughout the gap was more uniformly distributed.

The advantage in using impulses of short duration is to eliminate secondary effects and simplify the phenomena. Impulse breakdown in 0.3×10^{-6} secs. generally showed more uniformity throughout the gap, being the more marked with xylol.   The intense light is accounted for by the high ionization of the adsorbed gas moving to the anode, and further work with outgassed oil should prove illuminating as regards the early stages of breakdown. The importance of the removal of impurities can be gauged from the fact that 1 part of water in 1000 will lower the B.D.S. from 230 KV./cm. for pure oil to about 30 KV./cm.   This water can be removed either by centrifuging or filtering.   The dielectric strength is usually measured at 60–68° F. between $\frac{1}{2}$-inch. diameter spherical electrodes, separated 0.15 in.   The maximum stress is $\dfrac{V}{0.15} \times \dfrac{1.208}{2.54}$ volts/cm., and for good oil, at least 22 KV. (R.M.S.) should be required across the gap for breakdown : purer oil may require as much as 80 KV./cm. (max.) before the gap breaks down.

If the gradient at any particular point in the field exceeds the safe limit, partial breakdown of the oil occurs which corresponds with the corona effect for air.   Peek has shown that the gradient for this to occur in oil with

the concentric cylinder arrangement is

$$g = 36\left(1 + \frac{1\cdot 2}{\sqrt{r}}\right)\text{KV./cm. max.,}$$

which, in form, is similar to that for air, g depending on the radius of the inner cylinder. Further increase of voltage results in sparkover which, as in air, is self-healing. It should be stated here, that the B.D.V. is determined not only by the maximum value of the voltage as for air, but in addition, by the R.M.S. value and the shape of the wave. Again, unlike the case of air for which there is no effect, increase of frequency tends to increase B.D.V., although at high frequency there is a marked decrease in B.D.V.
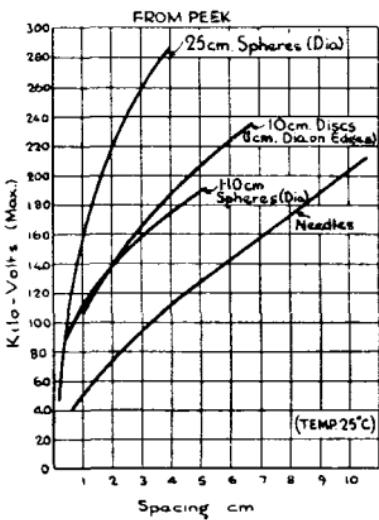
FIG. 32.—Sparkover of various shaped electrodes in oil at 60∿.

Peek's curves show the relation between the 60-cycle sparkover voltage and spacing for various type of electrodes. They are similar to those for air, even at large spacings, hence the same effects must occur during each type of breakdown, such as space charge, movement of liquid induced by the discharge (cf. electric wind), etc.

It is common to find large variations in sparkover voltage. Thus Goodlet, Edwards and Perry got a variation of 17 per cent. with good oil at large spacings, their scattering of results following the ordinary probability law. Peek got results much of the same kind, and showed that these variations persisted, even if the oil was changed after each sparkover : thus proving that

the effects of the sparkover were not of themselves influencing the scattering of results. It is quite conceivable that short-time breakdown values might, by preventing secondary effects, considerably reduce the scattering. The effect of pre-stressing the oil is generally to reduce the value of B.D.V. as with solids. Where the electrode system is such as to give some sort of preliminary discharge during the pre-stressing stage, the B.D.V. appears to be independent of the quality of the oil, provided that spacings above the critical value are used.

If, however, no preliminary discharges occur prior to breakdown (at large gap spacings), the electric strength is found to be proportional to the gap spacing. By proper positioning of barriers of solid insulating material in the gap, the B.D.V. can be considerably increased. Their effect is undoubtedly to limit the ion streams which flow between the electrodes, and break up the electrolytic conducting chains, thus making the ion paths much longer. The work of Goodlet, Perry and Edwards along these lines has shown that for short-time breakdown, barriers are effective only when pre-discharge occurs before actual breakdown, and then only if placed in contact with the discharging electrode.

When placed in any other position in the gap, they have no effect. Caution must be taken in their use, as they are liable to damage, particularly in the case of long-time discharges.

The effect of temperature is generally to decrease B.D.V. In the case of transformer oil, however, there is first an increase up to about 70° C., followed by a decrease above this temperature. The above authors show that the percentage increase may be as high as 50 per cent. for the small spacings. At large spacings the increase prevails only where pre-discharges do not occur ; if they do, the effect reverses or does not appear at all.

The effect of increase of pressure for liquids is much the same as for gases—increase in dielectric strength. The work of Friese indicates a B.D.V. of 90 KV./cm. per atmosphere for transformer oil with much prospect of higher values for the purer hydrocarbons.

VACUUM AS A DIELECTRIC

PASCHEN's Law no longer holds when the product press (mm.) × sparking distance (cms.) is less than about 1. For the case of electrodes separated 1 cm. apart, this would correspond with pressures of about 1 mm. and lower. Further, the work of Meservey shows that the corona voltage at these low pressures can be extremely high, the voltage increasing very steeply, even for small diminutions in pressure. The characteristic, then, of low-pressure discharges is the high voltage necessary to start them.

This can readily be explained on the basis of the classical kinetic theory, for the mean free path of the molecule (or ion) is inversely proportional to the pressure ; thus at 10^{-3} mm. Hg an air molecule has a mean free path of some tens of centimeters, and at still lower pressures a condition of affairs exists where the molecular path is many times that of the dimensions of the discharge vessel. The ionization by collision process which was necessary to account for the case of an air discharge at atmospheric pressure, will, at these extremely low pressures, have little or no say whatever in the conduction process. Although the molecules move on the average tens of centimetres before meeting other molecules, yet the number of molecules per c.c. left in the evacuated space even at the lowest pressures of about 10^{-8} mm. Hg which can be reached with present-day vacuum technique is still of the order of 10^8—a

considerable number. These, if suitably excited, are capable of carrying hundreds of amperes across the inter-electrode space.

In comparison with other dielectrics, high vacuum is free from leakage, at least, until gradients of the order of 10^5 volts/cm. or higher are reached, and does not appear to be affected by such factors as temperature, frequency, etc., which have rather marked and sometimes drastic effects in the case of solid or liquid dielectrics. The main condition required is that the vacuum shall not deteriorate, either by external causes, or through effects connected with the state of the electrode system. Some idea of the " electric strength " of a vacuum of about 10^{-6} mm. Hg pressure can be gleaned from the fact that in modern extra high-tension thermionic rectifiers, a potential difference of about 250 kilovolts can be impressed across a space of about 1 cm. between an outgassed cylindrical anode and a concentric filament system without any breakdown of the vacuum occurring.

When the impressed gradient becomes sufficiently high, of the order of 10^6 volts/cm., a new phenomenon occurs and the high vacuum exhibits an electrical leak. This is due to the action of the field in pulling electrons out of prominences on the cold cathode ; initially these electrons pass along the lines of force to the anode and constitute what are now known as the " Field or Auto-electronic Currents." All high vacuum effects are bound up with the presence of these field currents which will be fully discussed later.

It is interesting to point out in connection with these high gradients, that even in air at atmospheric pressure, it is possible for the gradient to be as high as 10^6 v./cm. without breakdown occurring in uniform fields across minute air gaps of about 10^{-4} cm. The experiments of Broxon on these lines show definitely that with a gap of $2\frac{3}{4}$ wave-lengths ($0\cdot546$ μ green line from mercury) Ohm's Law holds, and that gradients of over $1/2 \cdot 10^6$ v./cm. do not produce breakdown of the gap, although Wood had previously suggested that these high gradients

6

produce "*field current electron clouds*" up to distances of 30 wave-lengths of sodium light from the electrodes. However, Broxon was able to bring the electrodes together to within $\frac{1}{2}$ a wave-length before leakage across the gap occurred. This does not quite agree with the results of Wood, but, considering that field effects can enter, as in the case with breakdown of thin films previously discussed, when the gradient exceeds 10^6 v./cm., it is likely that Wood's results have more than passing significance, in that they were the first to suggest any such pure field effect on the electrodes.

When the voltage is increased above the point at which field currents are obtained, the vacuum breaks down in no uncertain manner in the form of an arc between the electrodes. This has all the characteristics associated with normal arc breakdown. When the amount of power available to support the arc is limited, as for instance, in the case of a charged condenser across the electrode system, so that the arc lasts for a short but definite time, it displays some rather general characteristics which have been described in detail by Gossling, who named this type the 'flash arc.' All that can be seen of the breakdown is a bluish-white scintillation on the cathode system, almost analogous to the cathode spot of the ordinary arc. In most instances the circuit can be so arranged that the discharge is aperiodic, or nearly so, thus allowing calculations of time of discharge, energy dissipated in early stages, etc., to be made.

The Vacuum Arc.—The difficulty of getting a low voltage discharge to pass at pressures below about 0·01 mm. Hg can be overcome by the use of an auxiliary electrode in the discharge vessel.

Thus, air at 10^{-4} mm. pressure will breakdown with only 80 V impressed between two iron electrodes separated 2 cms. apart, provided that a momentary auxiliary discharge from an induction coil be passed from the anode to some third independent electrode. The discharge takes the form of a sustained arc lasting for

a short time, usually a minute or so, between the two main electrodes, having been initiated in some rather complex way by the high voltage auxiliary discharge. Newman has examined low voltage vacuum arcs of this type in air, hydrogen and sodium, all being excited in the above manner. His pressures were usually in the region of 10^{-2} to 10^{-4} mm. Hg, though in the case of sodium the vacuum chamber was connected with the pump throughout. The brilliant white arc carrying 6–10 amperes in the residual air gases, oxygen, nitrogen, carbon monoxide, carbon dioxide, hydrogen and water-vapour, when examined spectroscopically showed up the Balmer and secondary hydrogen lines in addition to a continuous spectrum from $\lambda6000$ to about $\lambda2000$.

It is rather interesting to note that there were no lines in the spectrum which corresponded with the material of the electrodes, so that the discharge was carried exclusively by gas ions, at least for the short intervals for which the arc could be run and observed.

Another type of arc which has recently been described by Tanberg is that which is 'drawn' in vacuum at pressures of the order of 10^{-4} mm. and thus does not require the aid of an auxiliary discharge to start it. The arc is 'drawn' or ignited by bringing the electrodes close together till they touch, so that withdrawing one from the other produces a very heavy current density at the last point of contact (actual current is several amperes). This ignites the arc, which is then controlled in the usual way by external series resistance. The characteristics of this type are much the same as for all arcs, having the usual cathode 'hot spot,' which by suitably shielding the electrode with a quartz tube, is only permitted to wander over a limited and small area.

The chief interest in this work centres round the results which have been obtained for the velocity of the vapour stream which leaves the copper cathode, and for the temperature of the 'hot spot.' The vapour jet velocity from the cathode, which reaches mean values of the order of 10^6 cms./sec., was determined by two methods :

(1) relation between the observed force of reaction of the vapour stream on the cathode together with the loss in weight of copper cathode ; (2) the relation between the force of reaction of the vapour stream on a light vane suspended 2 cms. in front of the cathode, together with the increased weight of the vane. This result has been confirmed by Berkey and Mason with a variation of the method of measurement. They measured the energy imparted to the vane by the vapour stream, from the rate of rise of temperature of the vane, taking all possible precautions in their temperature measurement. They found, furthermore, that the copper particles shot off from the cathode hot spot had acquired a positive charge and were not the neutral particles previously imagined. Further confirmatory evidence for the velocity of the vapour stream comes from the work of Kobel on the mercury vapour arc, where velocities of the same order were obtained. An explanation not altogether complete has been offered by Compton for the force of reaction on the cathode, by considering the value of the accommodation coefficient α of the positive copper ions striking the cathode. He estimates α in this case to be 0·9826, which means that over 98 per cent. of the energy of the ion is lost in the neutralization process at the cathode, and that the neutral molecule ultimately leaving the cathode does so with less than 2 per cent. of its initial energy. Calculation shows that even this small energy balance is sufficient to account for the reaction on the cathode, although it does not settle the question of the extraordinarily high velocity of the ions (or neutral molecules ?) which leave the cathode ; neither does the recent suggestion of Wellman, that the high velocity stream is brought about by interaction with the gas (evolved from the cathode during the running of the arc) fit in with the experimental facts (the pressure at the end of the arcing process does in some cases rise to something of the order of 10^{-2} mm.).

Another suggestion which awaits experimental proof is that the presence of a thin gas layer almost in contact

with the cathode spot furnishes the high velocity ions. This is not at all improbable when the appearance of the arc as described by Tanberg and Berkey is considered. Starting from the cathode, there is the cathode spot, with the cathode glow in close proximity to it ; then follows the dark space whose boundary defines the anode glow. Spectrographic observation of these various regions has yielded interesting results. Unlike the short-time arcs of Newman, the spectrum of the cathode spot indicated the copper lines due to the cathode, in addition to some iron lines due to impurities in the copper. The temperature of the cathode spot as observed with an optical pyrometer showed it to be in the region of 3000° K., a more or less accepted figure ; further study with the pyrometer showed that the temperature of the cathode spot was proportional to the current passed by the arc up to temperatures greater than 3000° K.

Confirmation of this temperature was obtained from the spectrum of the visible region in the vicinity of the cathode. This was faint but continuous, and had superimposed high intensity emission lines in general agreement with Newman's results previously stated. The anode glow, in addition to showing up the copper lines, indicated that mercury had somehow got into the discharge vessel, as some mercury lines were also present.

Schottky Effect. — The well-known equation of Richardson $i = AT^2 e^{-\frac{b}{kT}}$ defines the saturation current which may be drawn from any thermionic source in high vacuum, and where space charge effects, etc., do not arise. Thus in the case of any thermionic valve, on plotting the emission current against the voltage on the anode, for any fixed filament temperature, a stage on the characteristic is reached where further increase in anode voltage only gives negligibly small increase in anode current, which is then given by Richardson's equation as above.

The anode current thus never entirely saturates, but goes on increasing at a slow rate the higher the voltage

which is applied to the anode. This tendency to non-saturation has been explained on theoretical grounds by Schottky, and has been amply verified experimentally by many observers. He assumes that, in order that an electron of charge e may escape from the surface of the filament, some external force, in this case supplied by the external field, must counterbalance the force of attraction of the surface for the electron which tends to pull the electron back. This force has been shown to be given by the force between the escaping electron and its mirror image in the surface, so that by assuming that for some distance x from the surface, the two fields balance one another, $\dfrac{e^2}{(2x)^2} = \mathrm{F}e$, where $\mathrm{F} = $ field,

$$\therefore \ x = \tfrac{1}{2}\sqrt{\left(\dfrac{e}{\mathrm{F}}\right)}.$$

Thus, knowing the field at the surface of the filament, it is possible to find this critical distance for any particular field—the stronger the field the smaller is this critical distance, and vice versa. Calculation with values of F as high as 10^6 volts/cm. show that x has a value of about 20 atomic diameters.

The effect of the external field can be looked upon as reducing the work function ϕ of the metal of the filament. With the field acting, the amount of work necessary to be done on the emitted electron, in taking it from the surface of the metal to an infinite distance away, against the attractive force $e^2/4x^2$ of the rest of the metallic surface is diminished to an extent which depends on the value of the external force $\mathrm{F}e$, so that $\displaystyle\int_0^{x_0}\left[\left(\dfrac{e^2}{4x^2}\right) - \mathrm{F}e\right]dx$ defines the " effective " work function ϕ', hence

$$e\phi' = \int_0^{x_0}\left(\dfrac{e^2}{4x^2} - \mathrm{F}e\right)dx = e\phi - \mathrm{F}^{1/2}e^{3/2},$$

$$\therefore \ \phi' = \phi - (\mathrm{F}e)^{1/2}, \text{ where } \phi = \int_0^\infty\left(\dfrac{e^2}{4x^2}\right)dx - \int_{x_0}^\infty\left(\dfrac{e^2}{4x^2}\right)dx.$$

Substituting this value of ϕ' in the Richardson equation,

$$i = AT^2 \epsilon^{-\frac{e}{kT}[\phi_0 - (Fe)^{1/2}]} = I\epsilon^{\frac{e^{3/2}F^{1/2}}{kT}},$$

where $I =$ current for zero field.

From this it is seen that the $\log i$ and $\sqrt{F}$ relation should give a straight line when plotted. Schottky verified this for fields up to about 500,000 volts/cm., and quite recently it has been verified by De Bruyne for field strengths up to 10^6 volts/cm. It should be mentioned that the Schottky law only holds for clean surfaces, and cannot be applied to composite surfaces such as thorium or caesium on tungsten, etc., although thermionic currents with these surfaces likewise saturate poorly. Reynolds, Kingdon and Langmuir have investigated this failure to saturate of metal surfaces covered with adsorbed electropositive atoms (thoriated tungsten) and find the greatest
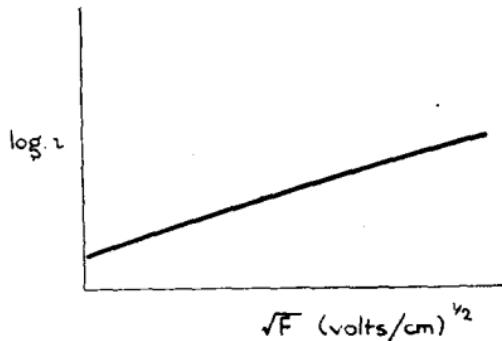
FIG. 33.

variations from the Schottky theory occur for fields below about 10,000 volts/cm., and the lower the working temperature. Above this value the observed curves lie on the Schottky line. They have further found that the closest agreement was obtained when the surfaces were either clean or almost wholly covered with thorium; and that the greatest variation occurred if the surface was about 70 per cent. thoriated. Neither the 'patch' nor the 'grid' theories of Langmuir and Becker respectively explain this increasing departure the lower the field strength, and, so far, no completely satisfactory explanation has been given. Becker and Mueller have recently applied the Richardson equation to find the

surface field at various distances from the composite
surface as follows :—

Since $\log_{10} i = \log A + 2 \log T - \dfrac{\phi' e}{2 \cdot 3 kT}$,

$$\dfrac{d \log i}{dF} = - \dfrac{e}{2 \cdot 3 kT} \cdot \dfrac{d\phi'}{dF} \; ; \; \text{but } \phi' = \phi - (Fe)^{1/2},$$

$$\therefore \dfrac{d\phi'}{dF} = - x_0,$$

$$\therefore \dfrac{d \log i}{dF} = \dfrac{e x_0}{2 \cdot 3 kT} = \dfrac{11600 \; x_0}{2 \cdot 3 T}.$$

Hence the slope of the $\log i$, F curve gives the distance x_0
from the composite surface, where the applied field
balances the surface field. They find that, as is to be
expected, the adsorbed electropositive atoms lower the
work function of the surface, producing large fields close
to the surface which assist the electrons to escape.
These fields apparently reverse in direction as the
distance from the surface increases and can be quite
appreciable even at distances of the order of 25,000
thorium atom diameters from the surface.

" **Field Currents.**"—When an electric field of sufficient
magnitude is applied between two cold electrodes in
high vacuum, a stage is reached when a current-indicating
instrument in the circuit will register the presence of
small unidirectional currents which flow between the
electrodes in the high vacuum. These currents, which
become manifest by the application of the field, have
been termed " field " or " auto-electronic " currents, and
arise from the extraction of electrons from the cold
cathode by the large applied field.

As long ago as 1897, R. W. Wood, working with two
cold platinum spheres of 1·5 mm. diameter in vacuum,
found that he could produce X-rays from the anode, if
the voltage between the spheres was high enough. This
shows that the cathode rays impinging on the anode
must have been produced as field currents from the
cathode. Further work by Millikan and Shackelford

showed that with clean tungsten electrodes in high vacuum, gradients as high as 50 KV./mm. were required before the first sign of breakdown as shown by the leak of a tilted electroscope occurred. Heating the electrodes to various temperatures resulted in pushing up the breakdown gradient correspondingly, till, after heating to 2700° K., no further breakdown occurred, even with a gradient of over 4×10^6 volts/cm.

Much the same sort of results were obtained by Hayden and Piersol, working with molybdenum spheres. In all cases it appears that the presence of " field currents " indicates the very first stage of high vacuum breakdown.

The appearance of the discharge phenomena has been carefully described by Gossling. When the electric system is viewed in the dark, nothing is visible when the smallest currents of less than 1 microampere are passing, and provided the voltage is low. This may perhaps correspond with the " dark current " stage of the normal air discharge. If, however, the voltage be increased so as to give larger currents, visible luminescent spots appear on the anode. The electron beam striking it can be thus localized, and, if the current is large enough, local heating of the anode may result ; in fact, cases of holes of over 1 mm. diameter being melted in a nickel anode have been recorded. At the same time, the glass envelope surrounding the electrodes is seen to fluoresce blue if of lead glass and green if of soda glass where it is bombarded by stray electrons from the cathode. The discharge itself appears to be unaffected and uninfluenced by residual gas pressures up to 10^{-4} mm. Hg, i.e. the free gas present does not take any part in initiating or maintaining the discharge. This has been verified by most observers, except Del Rosario, who found that he could not get the discharge to start even with gradients of over 10^6 volts/cm., unless free gas at a pressure of 10^{-4} mm. Hg was present. His results have, however, so far not been confirmed.

The origin of the discharge appears to be confined to one or two active spots on the cathode surface, where the

field is greatest, the activity of these spots varying with the time for which the discharge lasts. Thus it is not uncommon to find, that, starting with any particular field current, and keeping the voltage across the tube constant, the current will decrease with time and the intensity of the previously described fluorescence will also decrease with the decreasing current, until finally it may disappear entirely. This must arise from changes in the form of the emitting points, brought about either by positive ion bombardment or by some other sort of adjustment of the metallic surface. Calculation by Gossling, Fowler and Stern of the areas of the emitting points shows them to be of the order of 10^{-8}–10^{-13} sq. cms. and giving a current density of over 10^6 amps. per sq. cm. This high current density helps to explain the brilliant bluish-white cathode scintillations recorded by Gossling, when his circuit was so arranged that sufficient power was available to maintain the breakdown, once it had started.

Further calculation on orthodox lines of the apparent field necessary to start a current from the cathode, shows this to be of the order of 10^6 volts/cm. This figure is evidently much too low, as no allowance has been made for the increased field due to the surface irregularities. In fact, Schottky gives 100×10^6 volts/cm. as the field required to counterbalance the image field of an electron escaping from a plane surface ; the fields as calculated have thus to be multiplied by a fairly large factor before they can be assumed to be anything like correct. All these figures, of course, refer to a fairly clean surface, i.e. one not contaminated to any appreciable extent by surface impurities such as films of sodium, thorium, caesium, etc. These have the effect of enormously reducing the field required to give any particular current, by lowering the work function of the surface. Gossling, by coating his anode surface with sodium phosphate, and transferring the sodium from the anode to the cathode by electron bombardment, was able to show this marked effect on the field. The gradual elimina-

tion of the sodium from the cathode by long-continued discharge, resulted in a corresponding increase in surface field necessary to give any particluar emission. These films were stable even at 1600° K., a rather surprising fact, as, flashing to this temperature did not result in altering the characteristic. Their thickness as calculated appeared to be of the order of atomic dimensions.

It is interesting to note that so far, no positive ion field currents have been recorded even with potential gradients of 35×10^6 volts/cm.

Conditioning of Surface.—In all work on field currents the cathode must be conditioned (i.e. have its surface in some definite condition) in order that results can be reliably reproduced. To do this, two methods are available. The first is to draw a fairly large current from the fresh cathode surface (up to about 0·5 milliamp.) for some length of time. The passage of this current results in " forming " the surface for all currents lower than that which has been used, i.e. if curves are plotted showing the relation between log current and the reciprocal of the field, straight line plots are obtained. Moreover, all these points on the curve are reversibly reproducible, provided currents in excess of that which has been used for conditioning have not been drawn from the cathode. These lower currents can be drawn for considerable lengths of time before any permanent fatiguing effects appear to arise, so that, by proper " conditioning," several families of curves can be taken with the assurance that surface conditions have changed but little from curve to curve. The second method is to use heat treatment. This consists in heating the cathode in stages to various temperatures : 150° C. produces the " melting " or possibility of free two-dimensional wandering of the surface gas layers ; at about 400° C. the surface gas is ready to be evolved ; at about 800° C. the positive ion (sodium and potassium) emission from the cathode occurs, and at higher temperatures the surface assumes a more or less permanent condition,

where extremely high gradients are necessary to remove the electrons.

The early stages in the heating always produce such a state of affairs that smaller gradients are required for giving any particular value of current than when the surface is not heat treated, although the curves cannot lalways be reversibly reproduced, unless the current conditioning process is carried out again.

Field Current Characteristics.—The experimentally established law of the auto-electronic current discharge has given a relation of the form $I = K\epsilon^{-\frac{C}{F}}$ so that straight line plots are obtained between $\log I$ and $\frac{1}{F}$

FIG. 34.

where I is the measured current and F is the measured field, and K and C are constants. This law has been verified by nearly all observers of this phenomenon within the current range of 10^{-12} to 10^{-3} amps., although the results of Del Rosario do not agree with the others.
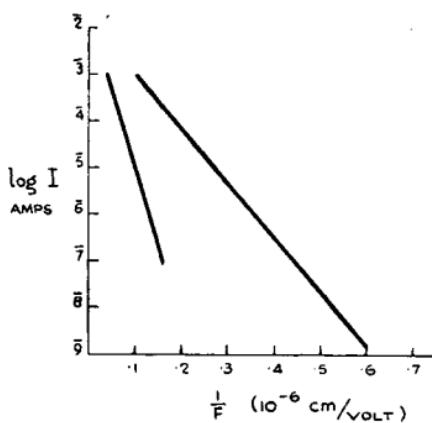
Further theoretical analysis of cold cathode emission by Fowler and Nordheim, based on the conceptions of the new wave mechanics, has confirmed the form of the experimental equation, and has shown that the space charge effect is negligible even with the heaviest currents drawn. Strictly speaking $\log \frac{I}{F^2}$ and $\frac{1}{F}$ should be plotted, although for most cases the discrepancies are negligible. They have also placed a lower limit of 10^7 volts/cm. for the fields necessary to produce this effect, which again fits in well with experimental facts. The form of the

equation is interesting, as it is entirely different from that for the Schottky effect with which it might have been expected to have something in common.

In the latter case the log I, $\sqrt{F}$ plot gave a straight line. If these two quantities are plotted for the auto-emission case, the resulting curve as found by Millikan and Eyring is concave to the axis of field, and certainly not linear throughout. Hence, the cold cathode effect does not follow the Schottky law which appears to be valid only for the case of thermionic emission and in fairly weak fields as compared with the fields necessary for field emission. The latter usually take place from one or two highly localized areas, where the gradient is so very high as to completely exclude the possibility of applying the image law. In other words, the constant C, which is proportional to the work function of the surface, is not at all altered by the influence of an external field in the cold cathode case, whereas it is distinctly diminished by the effect of the field in the thermionic case. This is rather important and will prove helpful shortly when the question of temperature effects have to be considered. The later careful work of Millikan, Eyring and McKeown on the field currents between clean points of tungsten, platinum, nickel and steel in the form of hyperboloids of revolution and a plane polished tungsten disc, have shown that there is a definite critical gradient at which for any particular point the current begins to appear. It is merely sufficient that this field be applied at the point, quite irrespective of the relations of applied voltage and distance, i.e. the normal log i, $\frac{1}{F}$ plot gave a straight line in any one case for various voltages and distances, showing that the gradient is the essential factor.

This particular electrode system lends itself rather nicely to direct calculation of the field at the point, by considering a limiting case of two coaxial confocal paraboloids of revolution between which the voltage is

applied.   Following Maxwell, it can be shown that the field E at the point $= \dfrac{2V}{r \log_e \left(\dfrac{2d}{r} \right)}$,

where r = radius of curvature at the point,
        d = distance between point and plane.

Hence, for any given field, i.e. for any given current, the relation between applied voltage and log of distance apart of point and plane should be linear. This is indeed found to be the case, and confirms previous observations.

log d

VOLTS
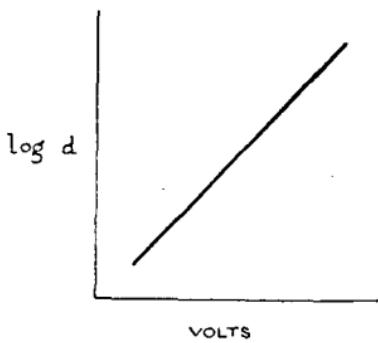
FIG. 35.

Field Currents : Temperature Effects.—The experiments of Gossling, Millikan and Lauritsen and others have shown that there is no temperature coefficient to be associated with field currents from tungsten points within the temperature range 300° K. to 1000° K. Above 1100° K. the latter observers have found a distinct dependence on temperature, so that the total current from the cathode is now made up of two parts— the thermionic current under the strong field which is given by the Schottky effect, and the field current upon which it is superposed.   The total current is thus given by

$$ I = AT^2 \epsilon^{-\frac{[e\phi - (e^3 F)^{1/2}]}{kT}} + A'F^2 \epsilon^{-\frac{C}{T + dF}}. $$

The difficulty in the experiment is to be able to isolate each current separately and observe its effect.   That the effect is real and permanent can be seen from Millikan and Eyring's work, where the observed currents at 1100° K. were about 10^{-4} amperes, whereas the thermionic current after allowing for the Schottky effect was only 10^{-12} amperes.   The temperature dependence was again

verified by Millikan and Lauritsen, as seen from the form of their curve (Fig. 36).

Up to about 800° K. there is little or no rise in current ; but at about 1100° K. the current has increased by about 20 per cent., although the thermionic portion of it contributes something considerably less than a fraction of 1 per cent.

At higher temperatures, of course, the thermionic emission is very large and completely masks the field emission.

The most recent work—that of Ahearn, in this connection, while not entirely disproving the temperature effect, shows that in the case of clean tungsten and molybdenum cathodes no such effect could be detected up to temperatures of 1400° K.

FIG. 36.

This non-dependence of the field current with temperatures up to over 1000° K. is somewhat difficult to explain from the point of view of classical dynamical theory, where the mean electron energy was supposed to vary directly with the absolute temperature, and the bulk of the electrons had velocities very close to the mean value, according to the classical gas laws. The later modifications of Drude's electron gas theory by Sommerfeld and the introduction of the new statistical mechanics by Fermi and Dirac have shown that even at 0° Abs. the electrons take on a whole series of energy states, starting from zero energy for some particular electron and extending up to some critical velocity which appeared to be practically independent of temperature at all ordinary temperatures. The number of electrons having
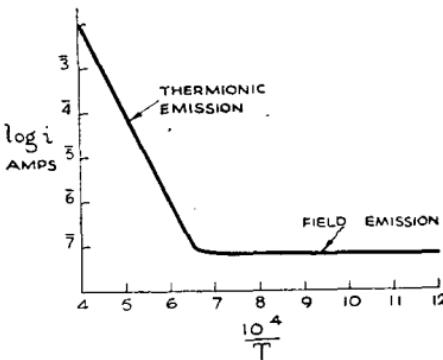
a velocity above this critical value was small at ordinary temperatures, but increased with temperature. At high temperatures the new distribution is found to blend into the old, which is then valid. This new type of electron velocity distribution, being so completely opposed to the classical view, is the fundamental difference on which the new mechanics has been built up—the electron gas now being termed " degenerate." The other difference consists in endowing the electron with characteristic wave-like properties on certain occasions and particle properties on others. Thus have many of the previous difficulties in connection with the behaviour of metals, such as specific heats, etc., been explained satisfactorily.

The applications of the new methods by Nordheim and Fowler to thermionic emission and to the extraction of electrons from cold metals by intense fields have led to some striking successes. The grounds on which the non-dependence on temperature of the field currents up to over 1000°K. have been established can be explained in terms of the groups of electrons having velocities near or at the critical velocity. These are the electrons which mainly give rise to the electrical conductivity of the metal; they also furnish the electrons for field current phenomena.

DISTANCE FROM SURFACE

FIG. 37.

In the latter case the electrons striking the surface normally, and having energy W, are considered as equivalent to a series of wave trains passing through the surface; the potential energy of the electrons then varies as shown. The electron loses energy C on passing through the surface, because it must have at least this energy before it can penetrate the surface. These authors give the emission current by the following formula :—
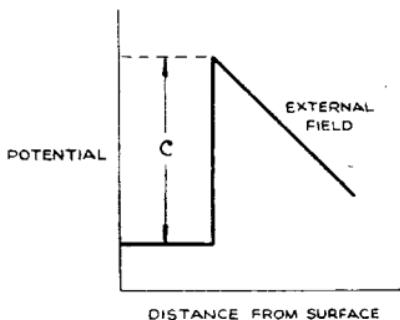
$$I = 6 \cdot 2 \times 10^{-6} \frac{\mu^{1/2}}{(\chi + \mu)\chi^{1/2}} \cdot F^2 e^{\displaystyle \frac{-6 \cdot 8 \times 10^7 \cdot \chi^{3/2}}{F}},$$

<div style="text-align:center">amps./cm.²</div>

where $\chi = C - \mu =$ thermionic work function,

$\mu =$ parameter equivalent to the thermodynamic partial potential of an electron,

$F =$ field.

This is readily seen to be of the same general type as the experimentally established field current equation.

The Flash Arc.—This is the type of vacuum breakdown obtained when energy at a sufficiently high potential, for example a charged condenser, is applied to two electrodes, spaced 2–3 mm., in the high vacuum. As its name implies, the resulting discharge is rather characteristic of an arc in that the breakdown is complete (but transient), and is attended by the appearanc of a brilliant white, yellow or blue scintillation on the cathode. It thus represents the most complete form of vacuum breakdown, the vacuum only being able to support 1000 volts or so during the passage of the discharge, which usually carries hundreds of amperes. One of its most interesting features is the " build-up " during the early stages. The work of Hull and Burger with tungsten electrodes, and later of Snoddy with copper electrodes, using the cathode ray oscillograph, has shown that during its early stages the discharge starts as a pure electron discharge, lasting up to less than 5×10^{-7} secs.

The current-voltage law as recorded by the oscillograph for this stage was such as to warrant the conclusion that the discharge starts as a 'field current' from the cathode, which in less than 10^{-7} secs. changes into the low voltage vapour arc. The rotating mirror method when applied by Snoddy for viewing the discharge showed the appearance of a luminous spot on the anode, due probably to the initial 'field current' bombardment and lasting from 1–4×10^{-7} secs. This may disappear if the discharge is not heavy enough. This was followed a little later by the cathode scintilla-

7

tion already referred to, which lasted throughout the discharge. The rather extensive work of Gossling on the subject, while confirming, in general, the above features, has shown that as much as 80 per cent. of the available energy may be required to be dissipated (provided always that the voltage be high enough) before the discharge starts. Using a peak voltmeter in the low voltage side of his discharge circuit (with known constants), he has been able to measure these transitory discharge currents of hundreds of amperes lasting for only a fraction of a microsecond.

As is to be expected, the intensity of the discharge depends on (1) the material of the electrodes and their surface condition, being for instance more intense with a nickel cathode than with a molybdenum one for the same previous treatment, (2) energy available for discharge. With any particular set up of electrodes it is usual to find the flash arc taking place at comparatively low voltage for the first discharges—15–20 KV. for 3 mm. clearances between copper anode and molybdenum cathode. This voltage progressively increases with the number of discharges passed through the system, until a stage may be reached at which 100 KV. will not produce breakdown. During the passage of these discharges the free gas pressure in the tube may increase quite appreciably, without having any marked effect on the discharge voltage in either direction ; however, if some of this gas is allowed to clean up electrically on to the electrodes inside the valve, a pressure change of 10^{-6} mm. being sufficient, a definite and consistent relapse to lower voltage is induced. This change is not at all permanent, as the voltage again progressively increases with further discharges.

Another important feature of the discharge, which Gossling has brought out, is the presence of a time-lag between the actual application of the voltage to the discharge tube and the appearance of the flash arc. If a discharge has been taken instantaneously at any particular voltage, then a reduction of the voltage by

3 per cent. is sufficient to cause a time-lag of the order of minutes before the discharge will again take place ; in fact, a ratio of at least 10/1 may represent two successive time-lags at any particular voltage. Such a result is undoubtedly connected with surface changes on the electrodes due to passage of the discharge, although the exact causes are not definitely known. In addition to these short time-lags, longer time-lags up to thousands of hours have been recorded in many cases. The explanations put forward by Gossling for the short time-lags assume that the field current, which, as was seen, initiates the discharge, is the responsible agent in bringing about a time-lag. In the first instance, the one or two minute spots on the cathode surface from which the field currents proceed are, by reason of the extremely high field there, under a severe electrostatic tension which may disrupt the surface. Thus, in the case of tungsten and with fields of the order of 10^8 volts/cm., this stress may reach values of several tons per square inch of surface. The subsequent slow yielding of the irregular mountain peaks is the contributing factor in the time-lag effect. When once the surface has broken in this way it can be expected to furnish further discharges under somewhat similar conditions, until the applied field is no longer able to initiate the field current. The surface is then fatigued for this particular field strength.

Again, it can easily be conceived (as an analogy with the Schrot effect in the case of thermionic emission), that the prime necessity for explaining the time-lag is the presence of an auto-electronic current above some fixed critical value which triggers off the discharge. The probability of any such spontaneous variation in the field current is such that the 10/1 ratio with 3 per cent. decrease in discharge voltage can be conveniently explained.

Whichever explanation is on the right track, it is interesting to record in this connection that in Gossling's experiments the presence of superposed auto-electronic

emission (of up to several hundred microamperes) at voltages below the discharge voltage for the system, did not greatly tend either to lessen the discharge voltage appreciably, or to make for regularity in the time-lags.

This is somewhat unexpected, in view of previous assumptions, but the unknown local conditions on the electrode surface are almost certain to play an important part in determining the resultant discharge.

ABBREVIATIONS TO JOURNALS

P.R.	= *Physical Review.*
P.R.S.	= *Proceedings of Royal Society.*
J.F.I.	= *Journal of Franklin Institute.*
J.I.(A.)E.E.	= *Journal of Institution (American) Electrical Engineers.*
Ann. der Phys.	= *Annalen der Physik.*
Zeits. f. Phys.	= *Zeitschrift für Physik.*
P.M.	= *Philosophical Magazine.*
P.C.P.S.	= *Proceedings of Cambridge Philosophical Society.*
C.R.	= *Comptes Rendus.*

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